THE FFG-7 FRIGATE
AN APPLICATION OF THE DESIGN-TO-COST CONCEPT.

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Monterey, California

THESIS

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by

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September 1978

Thesis Advisor: Michael G. Sovereign

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This thesis is the application of the concept of design-to-cost to the project of the FFG frigates. Using the available data relative to the major escort programs since 1950, a curve of force effectiveness vs. number of ships, similar to that presented by Vice Admiral Price in his congressional testimony on design of the patrol-frigate or FFG-7, was constructed and the results discussed.

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by

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ABSTRACT

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I. INTRODUCTION

As a consequence of a search for the most efficient use of the Navy's shipbuilding resources, the "high-low" mix concept was developed, meaning that expensive and highly versatile ships should be combined with moderately priced ones. Although with lesser capability, these could be produced in larger numbers to provide a greater coverage of the ocean and control of sea lanes. The FFG-7, initially called "patrol-frigate," was conceived and designed to represent a part of the "low" portion of this concept. The threefold capability of this ship would be:

(1) to detect and attack submarines both at long and short range and decoy a launched torpedo away from its target;

(2) to destroy anti-shipping missiles launched from subs, aircraft or surface ships;

(3) to destroy enemy surface targets with the own anti-shipping missiles.

Since this ship is not required to fulfill missions such as to escort carrier task forces, which are appropriate for much larger and faster ships like the multipurpose destroyer, it would have a much simpler command and control system and less speed. Under these circumstances a ceiling cost was established from the very beginning. Also, in order to counter the increasing cost of manpower, a limit of 185 was

imposed on the level of accommodations. This implied the transfer to shore of certain normally shipborne maintenance functions and related inherent changes in maintenance philosophy. This was one of the main reasons why the Italian-designed OTO MELARA 76/62 MM gun was chosen since its automation enables an additional cut in personnel. The same reason led to the adoption of gas turbine engines for the propulsion system.

The Design-to-Cost (DTC) philosophy[1] was applied during the preliminary design in that four main constraints have been considered:

(1) Cost
(2) Displacement
(3) Size of Crew
(4) Capabilities

Considering these four constraints, the problem consists in finding out the combination of displacement and the related number of ships which will maximize the effectiveness of that force for a given fixed budget. This goal can be achieved by trading off between the ship's capabilities, cost and production schedule.

Concerning the lead ship of the class, the "OLIVER HAZARD PERRY," it can be argued that the cost constraint was not respected. Actually, the stretching of the program along some ship characteristics changes and extra increasing costs of labor claimed the responsibility for an increase in cost

for the average cost of follow ships from the $45.7 Mi originally predicted to $68 Mi now expected.

The second constraint was also not fully respected. The FFG-7 class exceeds slightly 3,500 tons, somewhat above the original 3,400, but still below the "KNOX" (FF-1052) class and practically the same as the "BROOKE" (FFG-1, formerly DDG-1) class.

The third constraint was also not respected as the final complement was fixed at 185, a little above the initial limit of 174. However, the degree of automation achieved enabled saving nearly 65 men compared to the FFG-1 class. Moreover, the ship will have as many or more people available for maintenance because of the saving in watch standers.

The fourth and last constraint, the one imposed on the capabilities, "Design to the Mission," was respected and due to the excellent antiair warfare capabilities and its quick reaction missile defense, these ships will be good complements to the already existing ASW-oriented "SPRUANCE" and "KNOX" classes. In regard to ASW, the FFG's rate below the others, with a small SQS-56 designed to detect targets in layer at closer ranges than the larger SQS-26 sonars that equip those ships. The situation will certainly improve when succeeding ships will receive a passive towed array sonar and the new LAMPS III helos will be available.

II. PROBLEM DEFINITION

A. ABSTRACT

The purpose of this study is to demonstrate a possible way that can be followed to determine how many ships and of which type will maximize the effectiveness of a force under a fixed budget.

In the congressional testimony of Vice Admiral Price in defense of the FFG-7 project, a slide was displayed showing a curve relating force effectiveness to the number of ships for a fixed budget (see figure 1). No information was given, however, concerning the method used in its derivation. Following the outline of the "Conceptual Model for Setting Design to Cost Goals" developed by M. Sovereign,[2] it will be attempted to trace a possible way leading to the construction of a similar curve, using data concerning past escort ships.

To develop the combined model that generates this curve three basic relationships are needed:

1. The Cost Estimating Relationship (CER) which will give the cost as a function of the performance, for the first unit. Thus, first unit costs are needed as well as a MOE for the performance.
2. The budget cost relationship or learning curve.
3. The force effectiveness relationship.

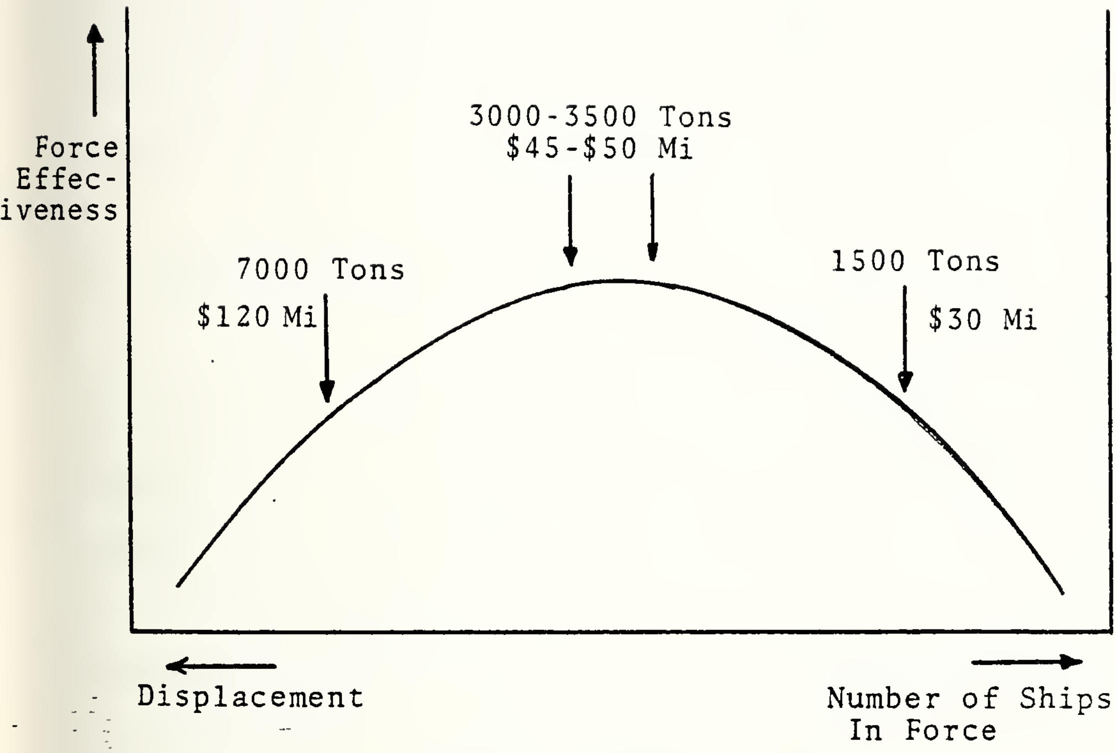


Figure 1. Vice Admiral Price's Curve

From those three relationships the curve of force effectiveness vs number of ships (or displacement) can be graphically obtained and its maximum determined as will be shown later.

This study will be divided in three parts, each corresponding to a chapter dedicated to each of the three basic relationships, followed by a final chapter dealing with analysis of variance, verification of the solution and conclusions.

B. GENERAL OUTLINE

1. Given the average unit costs for each type of ship in unadjusted dollars, it is necessary to convert them into constant dollars. For this purpose we will use the GELFER shipbuilding index, taking 1970 as reference.

2. Next, the average costs in constant dollars must be converted into first unit costs. Learning must be applied using for slopes of the respective curves the values given by NAVSHIPS Vol. III.3,[3] and the number of ships existent in each class.

3. The first basic relationship is a relation between first unit cost and some measure of the performance. Therefore, the calculation of a performance index is necessary. This was done following the general outline described in the Escort Ship Cost Model (ESCOMO).[4] A multiple regression was then executed using the performance index as explanatory variable for the first unit cost. The maximum speed and the

ship's complement were also considered. This last variable was discarded because of being highly correlated with the other two. Finally, in order to obtain a simple relationship between the index and the cost, these were adjusted for a reference speed of 30 knots.

4. The second basic relationship is given by the learning curve corresponding to the fixed budget available. For learning slop, the average of the values given by NAVSHIPS for seven different ships was adopted.

5. The third basic relationship was the most difficult to establish as there was no hint about the procedure used in the FFG-7 project. It was decided to evaluate the ASW and the Surface/AA effectiveness separately for each force. By force is meant the set of ships of each class that can be purchased with the fixed budget. For ASW, the MOE chosen was the radius of an ideal circular screen that could be formed with each force. This value was then multiplied by a corrective factor related to the ASW weapons on board, and a final ASW INDEX obtained.

6. For AA and Surface warfare purposes the "weight broadside" was the MOE selected to compare firepower among different forces. A gun firing shells with weight W at a rate r has a broadside of rxW. For missiles a tactic of shoot-look-shoot was adopted, since it is not likely that they would be fired with a faster rate.

7. Finally the ASW and AA/Surface warfare effectiveness indices were multiplied together to get a single combined set

of values. These values were then plotted against the performance index and a curve drawn through them. A maximum was defined or, more exactly an interval within which it would lay, and a most likely value was selected. The first basic relationship gives the corresponding first unit price and the learning curve gives the number of ships that can be built.

8. Some analysis of variance was carried out to determine intervals of confidence for both number of ships/displacement and cost per ship. It was also checked to see if the FFG-7 fits in the solution of the model and final conclusions were given.

III. FIRST BASIC RELATIONSHIP

A. COST ESTIMATING RELATIONSHIP (CER)

The first of the three basic relationships, relating cost and performance has been developed using the Escort Ship Model (ESCOMO),[5] a statistically derived model used to estimate the end costs of new escort ships.

This model uses as explanatory variables the characteristics of the platform such as speed, number of accommodations and endurance, weapon characteristics such as number and types of guns and missiles as well as characteristics of production like year of construction, quantity bought and number of builders.

The model as given in [6] and reproduced in Appendix A is not of direct interest for the purpose of this study, particularly in this chapter. For example, the second relationship, the learning curve, will deal with quantity while the adjustment of prices will eliminate the effect of the year of construction.

Also, the fact that ESCOMO uses Sonar and Ordnance Indices as well as speed and number of accommodations as independent variables will force modification of the model in order to obtain a direct relationship between costs and performance. To accomplish this goal, the following procedure was followed:

(1) The ASW and ORDNANCE indices for each of the different types of ships available were computed according to the general method described in ESCOMO;

(2) The two indices were combined into one index;

(3) The relationship between costs adjusted for a certain year and the three variables - combined ASW/Ordnance Index, speed and number of accommodations - was investigated.

(4) Costs were adjusted for the two last variables, if both are significant, and a direct relationship between adjusted costs and the combined index was finally obtained.

This procedure is explained in detail in the next sections.

B. DATA

The data available encompasses the most important types of cruisers, destroyers and frigates sized between 1000 and 8000 tons built in the U.S.A. during the fifties, sixties and first half of the seventies. Tables I (Frigates), II (Destroyers) and III (Cruisers), show the types of ships selected. Table I includes the FFG-7 and its characteristics, but no return costs are know for this ship, so far.

The return costs for DD 963 and DE 1052 are only approximated, many units being still under construction for the first class and it not having been possible to obtain the exact value for the latter. These would not have been available in 1972, when Vice Admiral Price's curve was established.

Table I. Post WWII U.S. Frigates, Destroyers, and Cruisers
(Frigates)

Name Class	DEALEY FF 1006 (DE 1006)	BRONSTEIN FF 1037 (DE 1037)	GARCIA FF 1040 (DE 1040)	BROOKE FFG-1 (DDG-1)	KNOX FF 1052 (DE 1052)	PERRY FFG-7 (PF 109)
Year Operating	54-57	63	64-68	66-68	69-73	78-84
Number of Ships	13	2	10	6	46	--
Displacement	1,914	2,650	3,400	3,426	3,965	3,605
Length	314.5	311.5	419.5	414.5	438	450
Beam	36.8	40.5	44.2	44.2	46.7	45
Draft	13.6	23	24	24	24.8	23
Power	20,000	20,000	35,00	35,000	35,000	40,000
Type	Steam	Steam	Steam	Steam	Steam	Gas Turbine
Speed	25	22	24.5	27	27	29+
Complement	170	220	241	248	220	185
Guns	4-3"/50	3-3"/50	2-5"/38	1-5"/38	1-5"/54	MK75 76ww
Missile Launcher	None	None	None	1 MK 22		MK 13 70D4
ASW	2 MK 32TT	ASROC 2 MK 32TT	ASROC 2MK 32TT	ASROC 2-MK 32TT 2-MK 25TT	ASROC MK 32TT MK 25TT	2-MK 32TT
Helo	No	Yes	Yes	Yes	Yes	2 Lamps III
Sonar	SQS-29	SQS-26	SQS-26	SQS-26	SQS-26	SQS-53
Average Cost Per Unit (1970 Dollars)	16.0	25.9	25.5	33.5	31.5	---

Table II. Post WWII U.S. Frigates, Destroyers and Cruisers
(Destroyers)

Name	SHERMAN	ADAMS	SPRUANCE	
Class	DD-931	DDG-2	DD-963	
Year Operating	56-59	60-64	75	
Number of Ships	18	23	30(a)	(a) expected
Displacement	4,050	4,500	7,180	
Length OA	418	437	560	
Beam	45	47	54	
Draft	20	20		
Power	70,000	70,000	90,000	
Type	Steam	Steam	Cogag	
Speed	32.5	32	30+	
Complement	304	354	260	
Guns	3 - 5"/54 4 - 3"/50	2 - 5"/34	2 - 5"/54	
Missile Launchers	None	1 - MK 11	Sea Sparrow	
ASW	2 MK 32TT	ASROC 2 MK 32TT	ASROC MK 32TT	
Helo	Yes	Yes	Yes (2)	
Sonar	SQS-23	SQS-23	SQS-26	
Average Cost Per Unit (1970 Dollars)	37	48.5	55(b)	(b) assumed

Table III. Post WWII U.S. Frigates, Destroyers and Light Cruisers
Light Cruisers (Former DDG)

Name Class	COONTZ DDG-37 (DLG-6)	LEAHY CG-16 (DLG-16)	BELKNAP CG-26 (DLG-26)
Year Operating	60-62	62-64	64-67
Number of Ships	10	9	9
Displacement	5,800	7,800	7,930
Length	512	533	547
Beam	52.5	54.9	54.8
Draft	25	24.5	28.8
Power	85,000	90,000	(?)
Type	Steam	Steam	Steam
Speed	34	32.7	34
Complement	375	396	418
Guns	1 - 5"/54	4 - 3"/50	1 - 5"/54 2 - 3"/50
Missile Launchers	1 MK 10	2 MK 10	1 MK 10
ASW	ASROC 2 MK 32TT	ASROC 2 MK 32TT	ASROC 2 MK 32TT
Helo	Yes	Yes	Yes
Sonar	SQS 23	SQS 23	SQS 26
Average Cost Per Unit (1970 Dollars)	65.2	69.5	68.0

Certain characteristics like speed, number of accommodations and others differ somewhat according to the source of information consulted. Whenever that happened the most reasonable value was adopted. Also, certain improvements or modifications that took place after the construction of the ships were not considered unless expressly mentioned.

This data was collected from the Jane's Fighting Ships and Jane's Naval Armament,[15] ESCOMO,[4] and Leopold's "Innovation Adoption in Naval Ship Design"[16].

C. COST ADJUSTMENT

ESCOMO uses as dependent variables the end costs of each ship in the data base. End costs are all of the funds that were expended from the Shipbuilding and Conversion, Navy (SCN) appropriation account to pay for each ship. Lead costs or costs associated with certain non-recurring investments such as initial plans and special facilities, are not included in the end costs, as well as research and development costs, R&D and training and support.

Tables I, II and III give unit average costs in unadjusted millions of dollars; as such they express the price levels existent at the time of construction of each class of ships. To correct for inflation these costs need to be converted into constant dollars. This can be done using the Gelfer index which was prepared by the Statistics and Special Reports Branch of the Comptroller Division of NAVSHIPS and includes both contractor furnished materials (CFM) and government furnished (GFM). (See Table IV and Figure 2.)

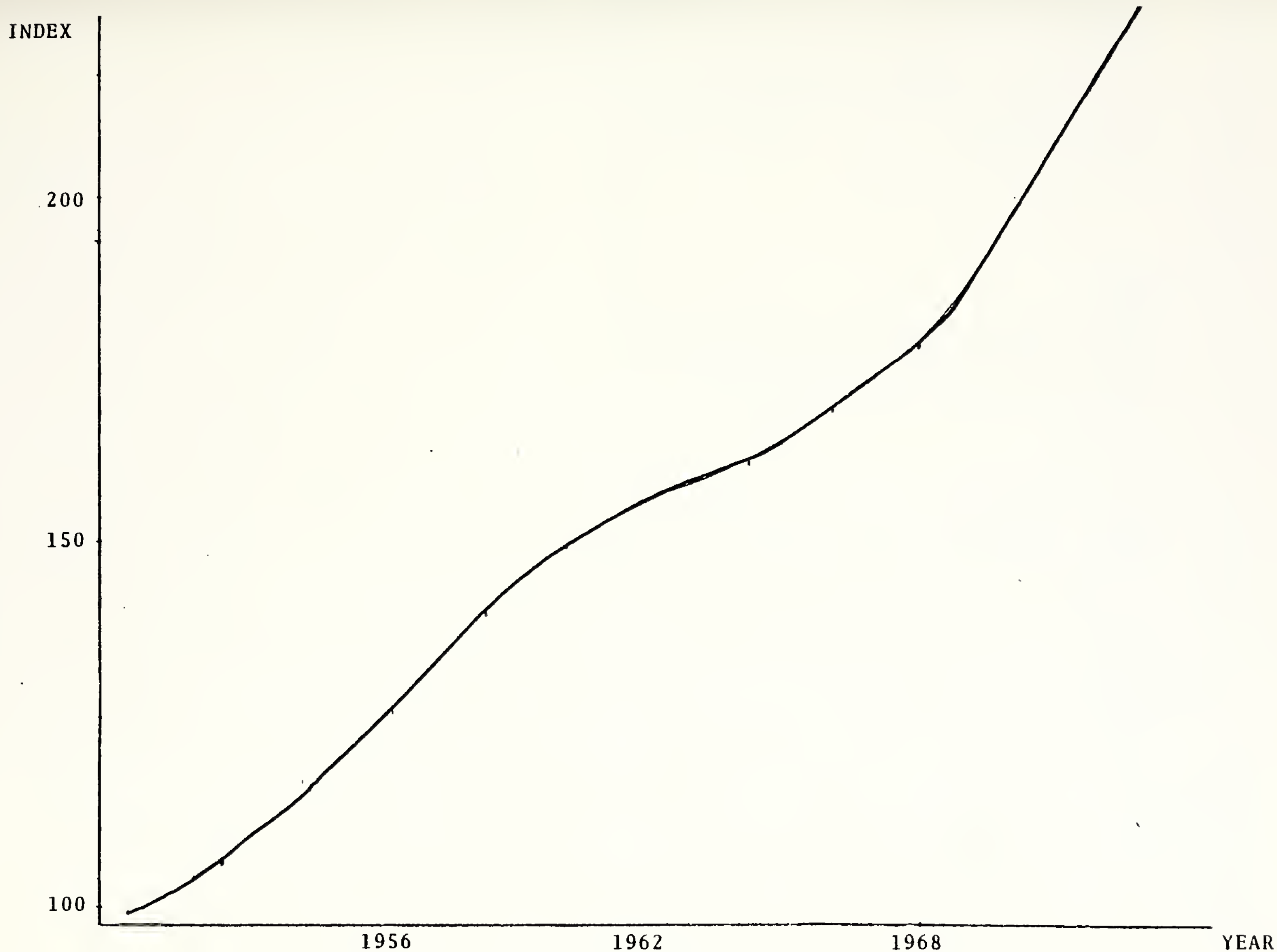


Figure 2. Gelfer Index

Table IV. Adjustment of Costs for Inflation Using the Gelfer Index

Type of Ship		Years of Construction	Gelfer Index	Non-Adjusted Cost	Adjusted Cost for 1970 (G.IND = 201.1)
1.	DE 1006	1955/57	125.6	10.0	16.0
2.	DE 1037	1961/63	160.0	20.6	25.9
3.	DE 1040	1964/68	166.5	21.1	25.5
4.	DEG 1	1963/68	162.6	27.1	33.5
5.	DD 931/45	1956/59	139.2	25.6	36.96
6.	DDG 2	1958/63	150.0	36.2	48.5
7.	DLG 6	1959/62	155.0	50.3	65.2
8.	DLG 16	1962/65	163.5	56.5	69.5
9.	DLG 26	1962/67	165.0	55.8	68.0
10.	DE 1052	1969/72	211	33.0	31.5
11.	DD 963	1975/--	360	101.2	56.0

D. COMPUTATION OF INDICES FOR WEAPON'S SYSTEMS

1. Sonar Index

The sonar index as conceived by ESCOMO is given by the quotient of the maximum range at which an underwater target can theoretically be detected by a given sonar divided by its average transmitting frequency. The choice of this index is based on the fact that sonar costs are directly proportional to the frequency, and also that size (that is volume and weight) has approximately the same relationship to these characteristics.[7]

The use of such an explanatory variable is, however, controversial since the maximum range is not a good measure of the performance. The figure of merit of the sonar would be a better index, according to some experts. Nevertheless, the ESCOMO index will be used.

2. ASW Weapons

Indices for ASW weapons are derived in an identical way to those for guns and missile systems and thus will be considered in the next section. Due to their relatively low GFM costs, ESCOMO did not develop indices for ASW torpedo tubes. Table V shows the computations of indices for the types of sonar existent on the ships being considered in this study.

3. Gun and Missile Systems

Indices for gun and missile systems can be obtained by multiplying range times number of components times bore

Table V. Computation of Sonar Indices

SONAR	DETECTION RANGE	FREQUENCY	INDEX
SQS-20	30 miles	11.0 KHz	2.8
SQS-23	40	5.0	8
SQS-26	80	3.5	22.9
SQS-53	100	3.5	28.6
SQS-56	30 (approx.)	4.5	6.7

diameter in inches. ESCOMO considered two general types of fire control (FC) systems or directors with the gun systems included in the data. We will consider here three types to extend the model to the more sophisticated systems in use. The less complex range-finding-radar and optical sights constitute the simplest gun system and will be weighted one-half. The intermediate system uses computers and a more complex radar system and will be weighted one. The third system will use highly sophisticated aiming system, and is weighted one and a half.

Example

The 1006 class escort has two 3"/50 gun mounts and one director of the first type. Thus, its index equals:

7.0x(2+0.5)x3 = 53 where seven is the range of the 3"/50; two is the number of gun mounts, 0.5 is the weighted value of the FC system; and three is the bore diameter of the 3"/50 gun.

The DD 931-945 carries three 5"/53 guns, two 3"/50 gun mounts and two of the more complex FC systems. The gun index will then be:

$$13.0x(3+1)x5 = 260$$

plus 7.0(2+1) 3 = 63, that is 323; where 13.0 is the range of the 5"/54 gun in miles, three is the number of 5"/54 mounts, one is the number of FC systems associated with this gun, and five is the bore diameter. Identically, 7.0 is the range of

the 3"/50 gun, two the number of mounts, one the number of FC systems associated with the 3"/50 battery and three the bore diameter.

The DD 963 uses one of the more sophisticated fire controls and two 5"/54 guns. Therefore, the index calculation gives us:

$$13.0x(2+1.5)x5 = 227.5$$

Surface missile systems indices (SMS) are calculated in a similar manner except that no weighting is given to any bore or missile diameter. The missile system components include launchers, FC systems or channels, weapon direction system (WDS) and 3-D air search radars.

The FFG-1 class ship carries a small 16-missile launcher, while the other missile ships carry launchers with approximately 40-missile capacity. These will be weighted as one and the former as 0.4 (16 divided by 40).

The DDG-2 class missile destroyer has a TARTAR missile system with one launcher, two fire control channels, one Navy Tactical Data System (NTDS) and one 3-D air search radar. Therefore, the SMS index is 17.5x (1+2+1.5+1) = 96. ESCOMO points out that the ASROC index should also be added to the SMS index. Thus, the SMS index for a DDG-2 destroyer is

96+10 = 106 since this ship has both a TARTAR and an ASROC.

4. Computation of a Global Index

Once having computed the Sonar, Gun and Missile indices following the procedure indicated by ESCOMO, a new problem is faced of finding a combined global index which would be representative of the performance of the ship concerning its weapon systems.

ESCOMO had already reduced the three indices to two by combining the gun and missile indices in the more general ORDNANCE index. For this purpose the gun index was divided by the bore diameter of the 5" guns and the result added to the SMS index. This did not change the relative differences between the 3" and 5" gun indices as they were divided by a constant. The division by five was done basically to avoid a possibility that would arise if the ORD index was greater for some non-missile ships than for missile ships. In this case an inverse relationship would result between end costs and ORD, what would be inconsistent since the GFM costs of missile systems would be greater than the gun systems.

To combine the Sonar and the ORD indices we faced a more difficult task as we were dealing with numbers of a different nature. After several attempts it was decided to add the gun index, the SMS index plus ten (for ASROC launcher), plus the Sonar index multiplied by two. A value of five would be added whenever one helo was available (two for the DD 963). This method gave more reasonable results when costs were regressed on this index and speed, this fact being the reason for preferring it to other alternatives.

Table VI shows the final results of these computations.

5. Regression Analysis

After having calculated the general index a few multiple regression models were run to determine the significance of the three indpeendent variables in explaining the costs. The three variables being initially tested are the global index, the speed and the ship's complement. The results are shown in the computer output (see Appendix A), and an extract is shown below:

Regression SS: 4323.702428 N=11
Error SS: 130.0335353 Total SS: 4453.735964
Residual Variance: 19.00479076
R Square: 0.9701299007

Beta	T-Statistics
-56.625	-2.6283
0.2074	3.7537
2.6341	2.1891
-0.0225	-0.2675

Variance-Covariance Matrix:

4.6417E+2	-7.6188E-1	-2.4840E+1	1.4011E00
-7.6180E-1	3.0513E-3	5.1652E-2	-4.3474E-3
-2.4840E+1	5.1642E-2	1.4479E00	-9.2603E-2
1.4011E00	-4.3472E-3	-9.2603E-2	7.0981E-3

F Ratio: 77.42954646 DF are: 3 and 7
Durbin-Watson: 1.667346079

As we see the value of R^2 is quite high (0.97) but only the index and the speed are significant, the t statictic for complement being very low.

From the correlation matrix we can observe that the variable complement is highly correlated with both speed and

Table VI. Computation of Global Performance Index

Item	Type	Sonar Index	Gun	SMS	SMS (+ASROC)	Sonar (x2)	Gun/5 + SMS+SONAR	Helo	Total
1.	DE 1006	2.8	53	0	0	5.6	16.2	0	16.2
2.	DE 1037	22.9	53	00	10	45.8	66.4	5	71.4
3.	DE 1040	22.9	165	0	10	45.8	85.8	5	90.8
4.	DEG-1	22.9	110	70	80	45.8	147.8	5	152.8
5.	DD 931/945	2.8	323	0	0	5.6	70.2	0	70.2
6.	DDG 2	8.0	195	98	106	16.0	163.0	5	168.0
7.	DLG-6	8.0	193	147.5	157.5	16.0	212.1	5	217.1
8.	DLG-16	8.0	63	210	220	16.0	248.6	5	253.6
9.	DLG-26	22.9	193	160	170	45.8	254.4	5	259.4
10.	DE 1052	22.9	130	54	30	45.8	135.8	5	140.8
11.	DD 963	30	227.5	91	101	60	206.5	10	216.5

index. It should therefore be removed and the new model observed. (See the Correlation Matrix and the results of the new regression below.)

Correlation Matrix

	1.0	2.0	3.0
1.0	1.0	0.525	0.876
2.0	0.525	1.0	0.835
3.0	0.876	0.835	1.0

Regression SS: 4316.721704 N=11
Error SS: 137.0142591 Total SS: 4453.735964
Residual Variance: 17.12678239
R Square: 0.9692361064

Beta	T-Statistics
-52.1762	-4.0515
0.1936	10.4337
2.3401	5.0824

Variance-Covariance Matrix:

1.6923E+2	8.2079E-2	-5.8991E00
8.2079E-2	3.6450E-4	-4.5062E-3
-5.8991E00	-4.5062E-3	2.1561E-1

F Ratio: 126.0225536 DF are: 2 and 8
Durbin-Watson: 1.658377947

The t-statistics for β_0, β_1, and β_2 are now all significant. The Durbin-Watson statistic is, however, somewhat low and indicates the presence of positive serial correlation. That could possibly be explained by some cumulative errors introduced by imprecision in cost adjustment. However, since the value (D.W. = 1.66) is not very low, this possibility will be ignored.

The values of the residuals are also reasonably low and, when plotted show no evident pattern (see Appendix A).

As we need a simple correspondence between unit costs and performance, it became necessary to remove the effect of cost variance due to the speed, that is, to adjust for speed. This was done by multiplying the coefficient of the speed by the difference between 30 knots and the speed vector. As a result we get a new cost vector F for the first unit costs of each class of ships, adjusted for constant dollars and speed.

Repeating the regression it can be seen that the effect of speed was practically completely removed.

Regression SS: 2471.804522 N=11
Error SS: 131.6188426 Total SS: 2603.423365
Residual Variance: 16.45235533
R Square: 0.9494439343

Beta	T-Statistics
18.0268	1.3998
0.1936	10.4337
0.0	0.0

F Ratio: 75.12008077 DF are: 2 and 8
Durbin-Watson: 1.658377947

The new model for single regression gave the following results:

Regression SS: 2471.804522 N=11
Error SS: 131.6188427 Total SS: 2603.423365
Residual Variance: 14.62431585
R Square: 0.9494439343

Beta	T-Statistics
18.0263	7.1486
0.1936	13.0008

F Ratio: 169.0201817 DF are: 1 and 9
Durbin-Watson: 1.658357964

Again, highly significant values for β_0 and β_1 were obtained as well as a linear relationship between costs and indices.

As an alternative approach, another model was tried in which exclusively missile ships were considered and all the steps executed before were repeated. The results for this model can be seen in the Appendix E. This model was not adopted in the development because it would not significantly change the results previously found. Besides, the full model is more trustworthy as it considers a larger quantity of ships.

Also as the average cost of the DD 963 is not exactly known and the value used is probably low, alternative models for higher possible costs were tried. Here, too, the model turned out to be relatively unaffected. All these results can be seen in the computer output - Appendix E.

6. Summary

In this chapter a linear relationship between first unit costs and a performance index was obtained. First unit costs are the costs adjusted to 1970 of the first ships of the two different classes of escorts being considered in this study. To find a performance index the methodology followed in ESCOMO[4] was used.

IV. SECOND BASIC RELATIONSHIP

A. THE LEARNING CURVE

As a result of empirical analysis it has been verified that cost-quantity relationships are fundamental in the procurement of naval ships. These relationships are required to adjust the average unit cost data to the first unit cost used in the derivation of the CER's or, in the present case, in the derivation of the frist basic relationships: first unit cost vs global index.

According to NAVSHIPS COST MODEL, Vol. III,[8] the influences that contribute most to continued cost reductions on a specific multi-unit ship procurement are:

(1) Individual worker's learning or improvement involving increasing familiarity with tasks, tools, engineering, supervision, etc...

(2) Supervision learning or improvement

(3) Engineering improvement

(4) Tooling improvement

(5) Material improvement

(6) Industrial engineering improvement

(7) Production control

The formula generally used is:

$$Y = a \times n^b$$

where

Y = cost per unit (either the average cost or the unit cost)

a = cost of the first unit

b = learning coefficient

n = number of ships

The learning coefficient b is obtained by the equation $b = \log S/\log 2$ where S is the slope of the learning curve, that is, the decimal fraction to which cost decreases when quantity doubles. The determination of the slopes of the learning curves has been done by subjecting the commercial bid-data, that is, contractor's estimate plus profit, to intensive computer analysis. This bid-data, relative to twenty-nine different classes of ships was selected from the NAVSHIPS Form 4282.2, UNIT PRICE ANALYSIS - BASIC CONSTRUCTION, which shipbuilders are required to fill. In this form, that can be seen in Appendix B, costs are divided into nine different construction or weight groups and three different categories - direct labor, direct material and overhead. The methodology followed in the compilation of this data is explained in detail in [9]. The choice between unit curve or cumulative average curve was decided on the basis of "Goodness of fit." It turned out to be the cumulative average that looked more satisfactory.

Finally, the slopes for the totals of direct labor hours, material dollars, and total cost were calculated for each of the following nine weight groups:

(1) Hull structure
(2) Propulsion
(3) Electric plant
(4) Communication and control

(5) Auxiliary systems
(6) Outfit and furnishings
(7) Armament
(8) Design and engineering services
(9) Construction services

These results are displayed in Appendix C. It can be seen that for groups 1 through 7 and 9, the values do not show significant variation from each other. However, group 8, design and engineering services, shows the steepest slope (many in the 50% to 60% range). This should be interpreted as a consequence of the nonrecurrence of one or more of the factors of production. To cope with this fact, group 8 was subtracted from the total of nine parts, and new slopes for the totals of direct labor hours, material dollars and total cost were calculated. The mean and standard deviation of the eight groups (1 to 7 and 9) were calculated and are shown in the Appendix C. These results show that the groups 1 to 7 and 9 do not justify a detailed part breakdown, while group 8 should be treated separately.

The methodology used for the computation of the learning curve was then to use the slopes for the totals of direct labor hours, material dollars and total cost and calculate: first, the slope of the total nine parts in the breakdown; second, the total minus group 8 and third, group 8 alone. This methodology according to [10] was used in the examination of over 800 learning curves from the sample relative to destroyers.

Appendix D shows the total mean and standard deviations of the slopes of the learning curves for the entire sample for each class of ships. From this table were extracted the values relative to the ships covered in this study and the mean and standard

deviations for the total of nine groups, nine minus group 8 and group 8. These values are shown in Table VII.

In the computations that follow, the average value of 94.6% for the slope of the learning curve for the total cost, that is, all nine groups, was adopted.

B. ADJUSTMENT OF AVERAGE COSTS FOR FIRST UNIT COSTS

From Table C, the values of the slope of the learning curves for the DD 931, DE 1040, DE 1052, DEG 1, DDG 2, DLG 16 and DLG 26 were taken. Only the DE 1006, the DE 1037 and the DD 963 are missing. For these the mean of the slopes known will be used; this procedure will introduce a certain error, hopefully now significant.

By using the expression:

$$TG = a \frac{Z^{b+1}}{b+1}$$

where $b = \frac{\log S}{\log 2}$,

a is the cost of the first unit,

Z is the number of ships,

and

TC is the total budget available.

The first unit costs are obtained. Table VIII shows the first unit costs for each class of ships. Those costs were used in Chapter II in the establishment of the first basic relationship.

Table VII. Means and St. Deviations of Slopes of Learning Curves

	Direct Labor Hours	Material Dollars	Total Cost
Total of All Nine Groups	Mean: 92.9 St. Dev. 1.03	Mean: 97.7 St. Dev. .84	Mean: 94.6 St. Dev: .717
Total Minus Group 8	Mean: 95.2 St. Dev. 1.16	Mean: 98.3 St. Dev. .39	Mean: 96.1 St. Dev. .67
Group 8	Mean: 61.4 St. Dev. 2.78	Mean: 64.3 St. Dev. 11.12	Mean: 60.32 St. Dev. 4.36

Table VIII. Computation of First Unit Costs

	Type	Non-Adjusted Cost	Quantity of Ships	Learning	b+1	b	First Unit Cost	Sp.	IND
1.	DE 1006	16.0	13	94.6	.920	-.080	18.07	27.2	16.2
2.	DE 1037	25.9	2	94.6	.928	-.080	25.19	26.0	71.4
3.	DE 1040	25.5	10	95.1	.928	-.072	27.93	28.0	90.8
4.	DEG 1	33.5	6	93.3	.900	-.100	36.06	28.0	152.8
5.	DD 931	36.96	18	93.9	.909	-.091	43.70	34.8	70.3
6.	DDG 2	48.5	23	95.3	.931	-.069	56.06	34	168
7.	DLG 6	64.5	10	94.6	.920	-.080	71.34	34.5	217.1
8.	DLG 16	69.5	9	94.8	.923	-.077	75.97	32.5	253.6
9.	DLG 26	68.2	9	94.8	.923	-.077	74.55	33	259.4
10.	DE 1052	31.5	46	94.9	.924	-.076	38.94	28	140.8
11.	DD 963	54.0	30	94.6	.920	-.080	65.22	30	216.5

C. THE LEARNING CURVE

Two learning curves, one for a total budget available of $3 Bi and the other for $2 Bi were drawn, both with a slope of 94.6%. The standard deviation of .72 will be used. (See Table VII. In Figure 3 such curves are shown.

Obviously a more accurate alternative would be to apply learning in separate to direct labor hours and to material dollars, for the total number of groups except group 8 than for group 8 alone, and finally add together the two values.

Unfortunately the data available (see table in Appendix D) applies only to seven of the eleven classes of ships we are dealing with. Thus, the overall average indicated above will be applied to the total costs.

D. SUMMARY

In this chapter the learning curves for a total budget of $3 Bi and $2 Bi were obtained. For slope of these learning curves, the average of the values that were obtained in a certain number of shipbuilding programs were used. Using the date found in [3], the value of 94.6% was computed.

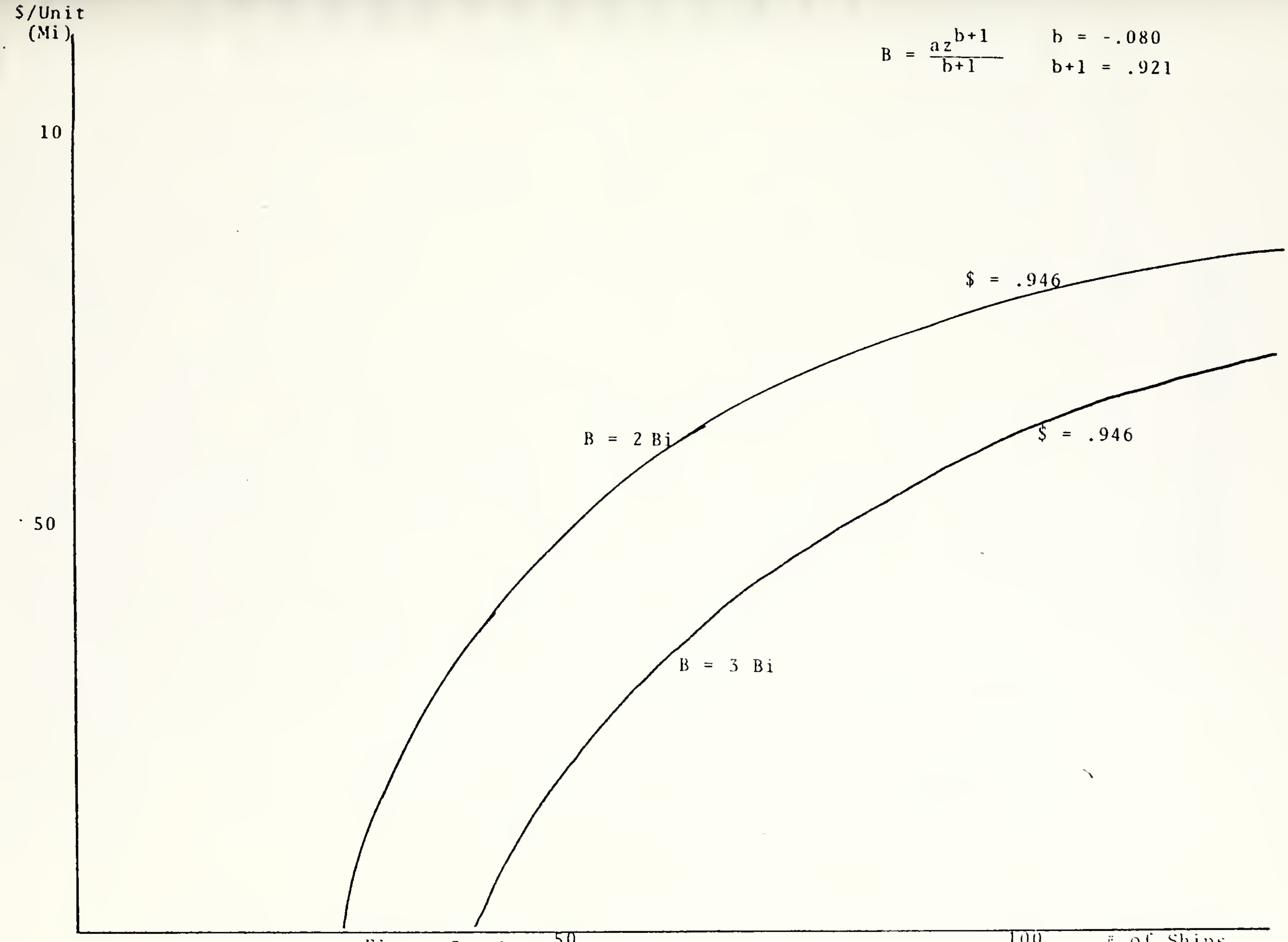


Figure 3. Learning Curves for $3 Bi and $2 Bi

V. THIRD BASIC RELATIONSHIP

A. FORCE EFFECTIVENESS

The force effectiveness relationship is the most difficult to establish. The objective is to quantify the combat effectiveness of the number of units which it is possible to buy with a certain budget. Sometimes this can be accomplished by multiplying an exchange ratio, eventually obtained from a simulation, by the potential number of enemy units to be killed. This is the normal procedure used for missiles, aircraft or tanks. However, with a naval force of such a complexity and diversity as the one that can be obtained with a budget of the amount being considered, the choice is between a relatively small number of large or medium-sized units with a reasonably large individual or unit combat capability and a larger number of smaller units with reduced armament and unit effectiveness. This is especially true when we consider multiple missions that not easily combine and sometimes even oppose each other. For example, a missile ship has certain constraints concerning orientation towards a thread axis which may interfere with the prosecution of an ASW mission. Another frequently observed interference regards speed and sonar effectiveness.

When the performances of the units in the force are or can be considered as independent, the individual performance can be multiplied by the number of units. More generally, however, a power relationship of the type $FE = Z \times X^r$ is used, where

FE is the total combat effectiveness in a certain type of mission

Z is the number of units

X is the measure of the performance of each unit

r is an exponent indicating saturation if $r<1$, that is, the effect of adding one more unit decreases with the number of units (Law of Diminishing Returns).

In this case $r>1$, there exists synergy, that is, the combination of a certain number of units achieves an effect greater than proportional to their number.

B. THE SIMPLIFIED COMBINED MODEL

The simplest relationship with which we can start is the one that shows:

(1) A linear CER with a single independent variable representing the performance.

(2) Neither synergy nor saturation, hence the force effectiveness is proportional to the number of units.

(3) Constant learning of average slope 94.6%.

The first condition is met in this study, as we have such a relationship as result of the regression model (See Part 2). We will assume that the second and third conditions are also met as other alternatives are difficult to establish.

Then, defining a special global index as a measure of the performance and multiplying it by the number of units that can be purchased with a given budget (obtained by dividing total cost or budget by average cost), the total force effectiveness for each class of ship was obtained.

In order to test the efficiency of the adjustment for speed, the procedure above indicated was executed for both costs non-adjusted and adjusted for speed. Table IX shows the results for the first case while Table X shows the same results for the second case. Plotting these values on a graph, it can be observed that the values non-adjusted for speed are widely spread, but after having been adjusted these values appear practically on a line, the non-missile ships DE 1006 and DE 1037 remain the only outlyers. This difference is still more evident if we restrict ourselves to missile ships. In this case the mean force effectiveness is 11700 with a standard deviation of 1412, while for adjusted costs the mean is 12081 and the standard deviation equals 286, that is, about five times less than before. Figure 3 shows the graph representing the third basic relationship for the case above mentioned using as measure of performance for each unit the ESCOMO INDEX calculated in III.D.4, and for a budget of $3 Bi.

C. THE FULLY COMBINED MODEL

1. Generalities

To deal with a more general case where there exists a more complex relationship between effectiveness and number of units and in the absence of a known or easily obtainable exchange ratio, a few MOE's were tested.

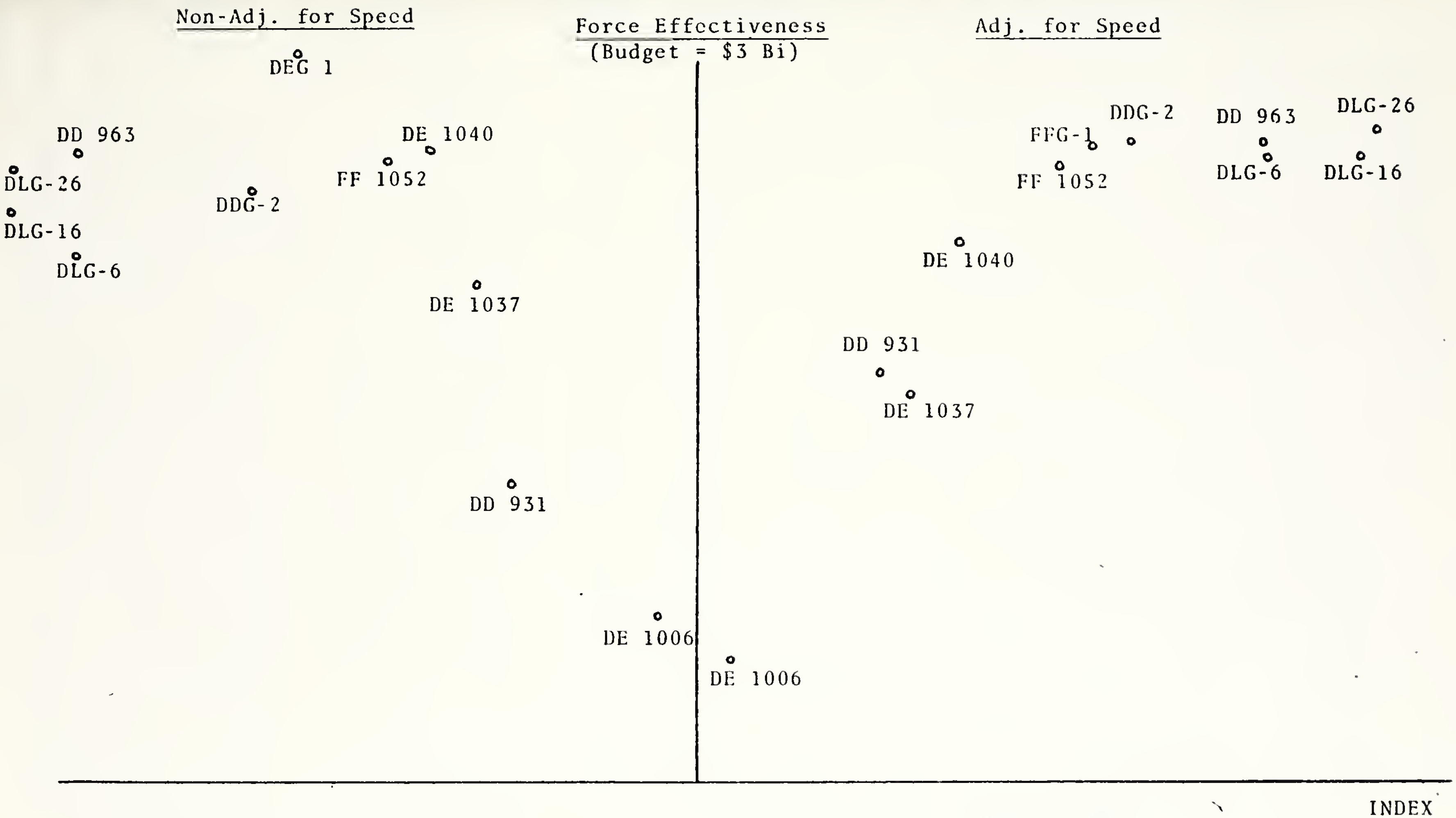
As a first approach, it was decided to deal separately with the ASW capabilities and the Surface or AAW capabilities.

Table IX. Force Effectiveness for Costs Non-Adjusted for Speed (Budget = $2 Bi)

Type of Ship	Year of Constr.	Gelfer Index	Non-Adj. Cost	1970 Const. $ Cost	Speed	Number of Ships	ORD Index	Prod.
1. DE 1006	54-57	125.6	10.0	16.0	27.2	188	16.2	3045.6
2. DE 1037	62-64	160.0	20.6	25.9	26.0	116	71.4	8282.4
3. DE 1040	64-68	166.0	21.1	25.5	28.0	118	90.8	10714.4
4. DEG-1	63-68	162.8	27.1	33.5	28.0	90	152.8	13752
5. DD 931	56-59	138.2	25.6	36.96	34.8	81	70.3	5694.3
6. DDG 2	58-63	150.0	36.2	48.5	34	62	168	10416
7. DLG 6	60-62	156.8	50.3	64.5	34.5	46	217.1	10098
8. DLG 16	62-64	163.0	56.5	69.5	32.5	43	253.6	10905
9. DLG 26	63-67	164.6	55.8	68.2	33.0	44	259.4	11440
10. DE 1052	69-72	211.0	33.0	31.5	28.0	95	140.8	13376
11. DD 963	75-...	310.8	54.0	54.0	30	55	216.5	11908
12. FFG 7								

Table X. Force Effectiveness for Costs Adjusted for Speed (Budget - $3 Bi)

Type of Ship	Year of Const.	1970 Const. $ Cost	Speed	Dif. (30-Speed)	Cost Adj. for Speed	Number of Ships (approx)	INDEX	TOTAL EFFECT.
1. DE 1006	54-57	16.0	27.2	(+) 1.8	21.63	139	16.2	2252
2. DE 1037	62-64	25.9	26.0	(+) 4.0	33.95	88	91.4	6283
3. DE 1040	64-68	25.5	28.0	(+) 2.0	20.52	102	90.8	9261
4. DEG 1	63-68	33.5	28.0	(+) 2.0	37.52	80	152.8	12224
5. DD 931	56-59	36.96	34.8	(-) 4.8	27.30	110	70.3	7730
6. DDG 2	58-63	48.5	34	(-) 4.0	40.45	74	165	12254
7. DLG 6	60-62	64.5	34.5	(-) 4.5	55.45	54	217.1	11725
8. DLG 16	62-64	69.5	32.5	(-) 2.5	64.47	47	253.6	11919
9. DLG 26	63-67	68.2	33.0	(-) 3.0	62.16	48	259.4	12451
10. DE 1052	69-72	31.5	28.0	(+) 2.0	35.54	84	140.8	12108
11. DD 963	75-...	54.0	30	0.0	54.0	55	216.5	11908



For Missile Ships Mean: 11700 St. Dev: 1412

For Missile Ships Mean: 12081 Stand: 286.4 (Reduced 21%)

Figure 4. The Simplified Model - Force Effectiveness

2. ASW Force Effectiveness

The definition of a measure of ASW effectiveness for the several "forces" composed of different types of ships involves basically the two following problems:

(1) For a budget as big as $2 Bi, the number of ships for every class is substantially large, never less than 30 units, thus more than the necessary for a usual formation. Besides, in a few cases the characteristics of both the Sonars and ASW weapons are very different. For example, different types of sonar (bow mounted or toward array) or the availability of one or even two helos, may add a powerful increment to the ASW capacity of several ships. All these difficulties handicap the comparison between effectivenesses of such a larger number of ships.

(2) The fact that appropriate exponents of synergy and/or saturation are unknown and difficult to obtain directly.

In face of these difficulties it was decided to use a relatively straightforward MOE in terms of the area of the ocean that could be covered with each force. More precisely, the radius of an ideal circular screen formed by the ships in each class was computed.

For distance between ships, the maximum theoretical sonar range divided by a constant to grant a fair overlapping was adopted. The value of five was selected as it seemed reasonable and yielded satisfactory results. For purposes of scaling these radius were divided by 50 and an index so obtained.

Concerning the ASW weapons, a different criterion was used, weighting with 100 the ASROC, 20 the torpedo MK-32TT and 10 the MK-25TT. The availability of the helo was weighted 30. All of the above weights will be added up and scaled dividing by 6000. The product of both indices, the one corresponding to Sonar capability and the one relative to the ASW weapons, are finally multiplied together and the result plotted against the global (ESCOMO) performance index. Tables XI, XII and XIII show these computations, while Figure 5 displays the graph ASW effectiveness vs global performance index.

3. Comments About the Curve of ASW Effectiveness

Analyzing the graph (Figure 5) it can be seen that four classes of ships are well ahead of the others in terms of effectiveness: DEG 1, FF 1052, DE 1040 and DE 1037. This can be explained by the following:

a. Due to their relatively low price, the number of ships belonging to the DE 1040 and 1037 is very high (80 and 102) and both are equipped with good sonars. The same happens with the more recent FF 1052 which is basically an ASW ship, well equipped for this type of mission, as well as with the DEG 1, both having similar characteristics, as both are equipped with ASROC, torpedoes and have helo facilities. The larger and much more expensive DLG 6, 16 and 26, have a smaller ASW effectiveness, as the number of ships in the force is much reduced (54, 48, and 47, respectively). Both the DDG 963 and the DDG 2 are at midway between the two former groups. If the

real price of the 963 is higher than the one used, then the total effectiveness would be smaller. In the graph another possible point for such a case is represented lying closer to the curve drawn through the given points.

b. Both the DD 931 and the now "old-fashioned" DE 1006, in spite of the large number of the DE 1006, cannot offer more than a low ASW effectiveness. The DD 931 is essentially a ship designed for surface and AA warfare. In fact, those ships underwent a major program of modernization to improve their ASW capabilities. Budget limitations only allowed this program to be carried on in eight ships of this class. Just for the sake of curiosity it was checked where a force of modernized DD 931 would be positioned on the curve represented in Figure 5. The modernization consisted essentially in the replacement of one of the 5"/54 guns by an ASROC launcher and of the SQS 29 Sonar by the SQS 23. The resultant new ESCOMO index was computed (actually it did not change much as the two changes cancelled each other), as well as the new force-effectiveness and the result plotted in the graph. A point closer to the possible curve than the original was found.

The exact definition of a maximum for the curve cannot be precise, as the curve itself is tentative. However, it can be stated that it must fall somewhere for an index between 80 and 140 or even between 100 and 120. A value of 120 will be adopted, which would correspond to a cost per ship (first unit) of $37.5 Mi (1970 dollars), and a number of ships of 107, considering a learning of 94.6%. Adjusting for 1973 this would correspond to a first unit price of $42.8 Mi and an average cost of about $32 Mi. (See Figure 6.)

Table XI. Computation of Sonar Index

	Sonar Type SQS	Effective Sonar Range (Max÷5)	Number of Ships	Product	$R = \frac{\text{Product}}{2\pi}$	R÷50	Perf. Index
1. DE 1006	29	3	139	417	66.40	1.33	16.2
2. DE 1037	26	8	88	704	112.10	2.24	81.4
3. DE 1040	26	8	102	816	129.94	2.60	100.8
4. DEG 1	26	8	80	640	101.91	2.04	152.8
5. DD 931	29	3 (4)*	110	330 (432)*	52.55 (68.8)*	1.05 (1.38)*	70.3
6. DDG 2	23	4	74	296	47.13	.94	168
7. DLG 6	23	4	54	216	34.39	.69	217.1
8. DLG16	23	4	47	188	29.94	.60	253.6
9. DLG 26	26	9	48	432	68.79	1.28	259.4
10. FF 1052	26	8	84	672	107.01	2.14	118.8
11. DD 963	53	10	55	550	87.58	1.75	216.5

*after modernization

Table XII. Computation of ASW Weapon Index

	GERF Index (ESCOMO)	PERF Index	A/S Weapon	Helo	Weapon Weight + Helo	# of Ships Adj. for Speed	Product	Scaling ÷6000
1.	DE 1006	16.2	2 MK 32TT	No	40	139	5560	.93
2.	DE 1037	71.4	ASROC 2 MK 32TT	No	140	88	12320	2.05
3.	DE 1040	90.8	ASROC 2 MK 32TT	Y(30)	170	102	17340	2.89
4.	DEG 1	152.8	ASROC 2 MK 32TT 2 MK 25TT	Y(30)	190	80	15200	2.53
5.	DD 931	70.3	ASROC 2 MK 32TT	N	40(140)*	110	4320 (15400)*	0.72 (2.57)*
6.	DDG 2	168.0	2 MK 32TT ASROC	N	140	74	10360	1.73
7.	DLG 6	217.1	2 MK 32TT ASROC	N	140	54	7560	1.26
8.	DLG 16	253.6	2 MK 32TT ASROC	N	140	47	6580	1.10
9.	DLG 26	259.4	ASROC (TERRIER)	Y(30)	130	48	6240	1.04
10.	FF 1052	140.8	ASROC MK 32TT MK 25TT	Y(30)	160	84	13440	2.24
11.	DD 963	216.5	ASROC MK 32TT	Y(2x30)	180	55	9950	1.65

*after modernization

Weights: ASROC: 100 MK 32TT: 20 MK 25TT: 10

Table XIII. Computation of ASW Effectiveness Index

Type	Sonar	ASW Weapons + Helo	Product	Perf Index
1. DE 1006	1.33	.923	1.43	16.2
2. DE 1037	2.24	2.05	4.59	71.4
3. DE 1040	2.60	2.89	7.51	90.8
4. DEG 1	2.04	2.53	5.16	152.8
5. DD 931	1.03 (1.38)	0.72 (2.56)	.76 (.994)	70.3
6. DDG 2	.94	1.73	1.63	168.0
7. DLG 6	.69	1.26	.87	217.1
8. DLG 16	.60	1.10	.66	253.6
9. DLG 26	1.38	1.04	1.44	259.4
10. DE 1052	2.14	2.24	4.79	140.8
11. DD 963	1.75	1.65	2.89	216.5

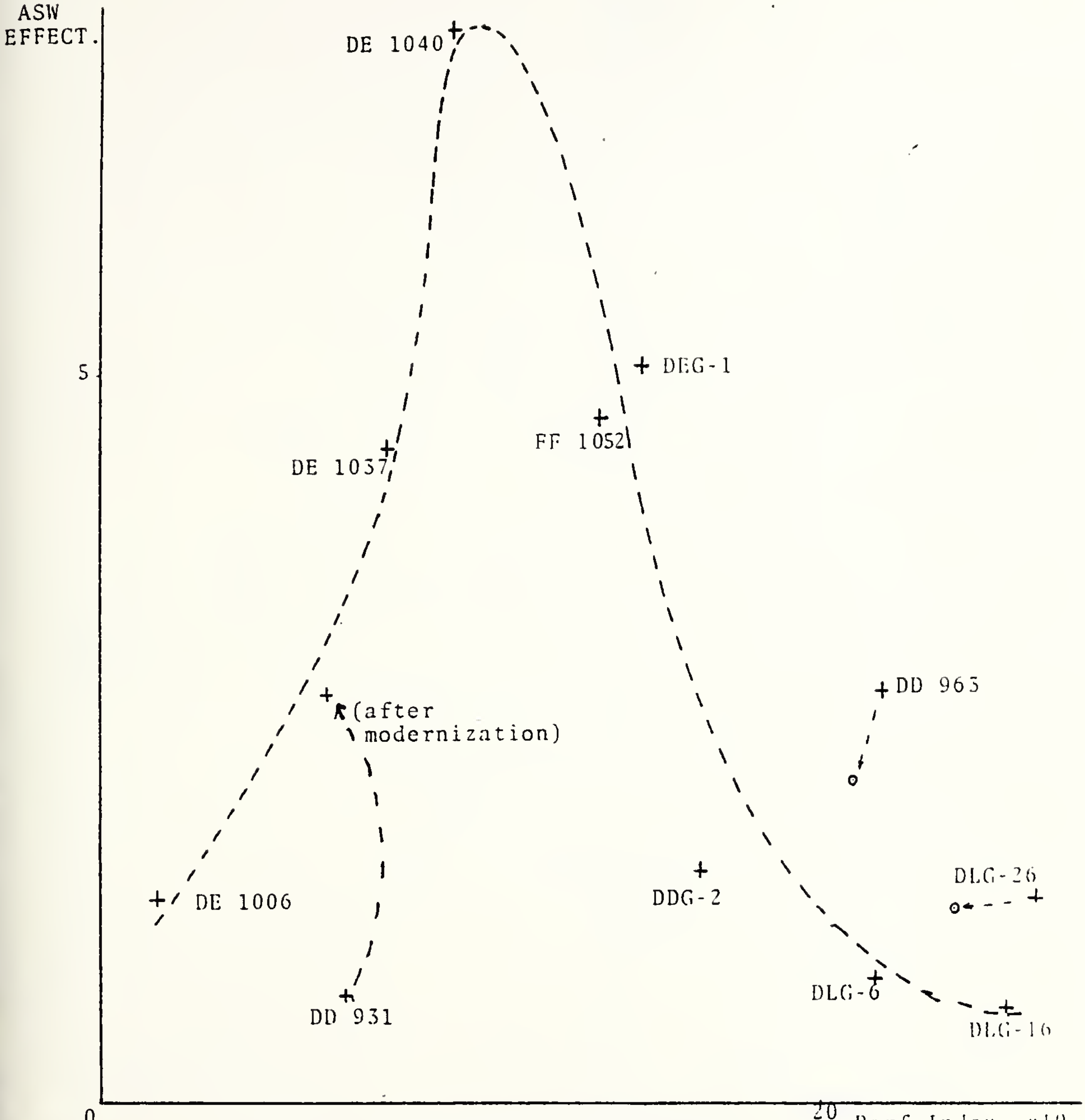


Figure 5. ASW Force Effectiveness

Budget 3 Mi
Only ASW Effectiveness

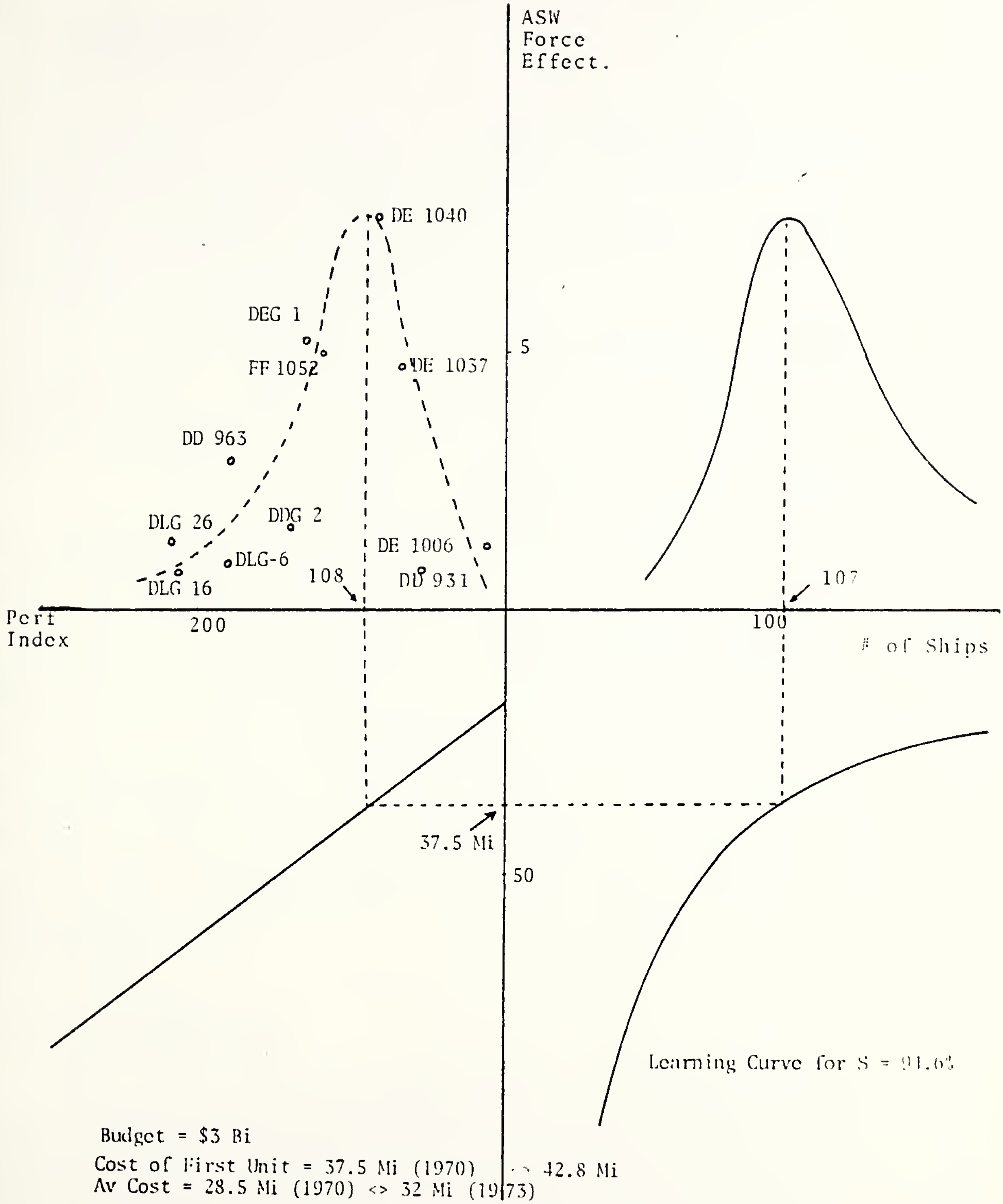


Figure 6. Design to Cost Model for ASW Warfare

D. SURFACE AND AA MEASURES OF EFFECTIVENESS

1. Generalities

The problem of finding an index representative of the effectiveness of the different classes in AA and surface warfares should be treated separately. However, the treatment of AA warfare offered a few problems:

(1) Difficulty in the establishment of a probability of kill. This probability would be variable with the target range and also with the type of weapon being used.

(2) The fact that some weapons like the IPDMS or the Standard Missile can be used against either surface targets, aircraft or missiles.

The first difficulty could not be removed with the consultation of a few models like the DePoy and Phillips model referred to in [10]. This model is a simplified one but it is not easily applicable to this study mainly due to the variety of weapons available aboard the ships being considered. Other studies perhaps more appropriate were not available because of classification.

2. Non-Aimed Fire

Basically we need a quantitative approach to compare firepower between defense platforms. Following the procedure recommended by A. Washburn in "Gross measures of Surface-to-surface naval firepower,"[11] we will use as our primary measure the "weight of broadside." A gun firing shells with weight W at a rate r has a broadside of rxW.

First it must be assumed that a shell must detonate within a distance D of a target to "kill it" and that D is proportional to the energy yielded (weight of explosive W) according to the expression $D = \alpha W^{1/3}$ where is a constant. Second a circular lethal area (πD^2) will be considered, the fire being directed randomly towards this area. Hence, the probability of killing the target is dependent on the total lethal area, which is proportional to $\Sigma W_i^{2/3}$, where W_i is the energy yielded on the i^{th} round. Therefore the measure of effectiveness more appropriate is $r.W^{2/3}$, which places less emphasis on big rounds.

As W scales with B^3, where B is the bore diameter of the gun, $r(B/8")^2$ will be used as the measure of effectiveness for any target and will be designated by "rate of fire in equivalent 8" rounds" (E8R).

The table below shows the "equivalent 8" rounds" for the types of guns considered in this study.

	3"/50	5"/54	5"/38
Rate of fire	15	40	15
E8R/Equiv.	2.11	15.63	5.87
Max. range	8	15	10

For such systems as torpedoes and missiles, a conversion to E8R was made based on the weight of explosive in the warhead. However, it must be taken into consideration that the use of guided missiles is not supposed in circumstances of "brute force."

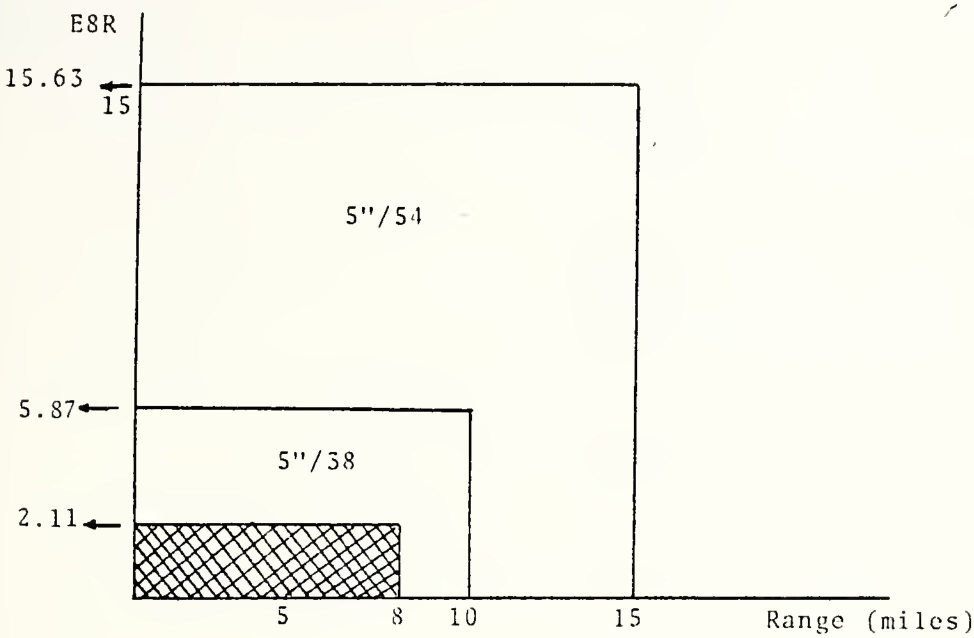
3. Aimed Fire

For bombs and shells the E8R can be converted into a measure of aimed fire power or effectiveness (AFP) by dividing by the square of the circular error probable (CEP). For independent repeated shots at a point target, with normally distributed errors, the probability of kill is $p_k = 1-.5^x$ where $x = \Sigma R_i^2$ and CEP_i is the radius of the circle equally likely to contain or not contain the i^{th} shot. As R_i^2 is proportional to $W_i^{2/3}/CEP^2$ and $AFP = \frac{E8R}{(CEP)^2}$.

Following Reference 12 a CEP of .01R is assumed for shells including fire control errors as well as dispersion, if CEP is measured in tenths of a mile, then AFP = E8R for aircraft and $AFP = E8R/(R/10)^2$ for guns.

4. Scalar Measure of Effectiveness

The graph E8R vs Range was chosen as representation for effectiveness. Although the areas of the corresponding rectangles are not expressed in operational units, they are nevertheless the more appropriate measures of effectiveness. These areas are represented in figure 7 and will be used as the measure of striking power for each gun. The same methodology will be followed for missiles, except that a rate of fire of shoot-look-shoot will be considered. The areas given by range in miles vs rate of fire in number of shots per minute are no longer rectangles and are shown in Figures 7 to 10. As minimum distance of fire was considered 1 mile for both TARTAR and TERRIER and .5 for the IPDMS (NATO SEA SPARROW) installed aboard the FF 1052.



For 3"/50 gun Area = $A_1 = 2.11 \times 8 = 16.88$

For 5"/54 gun $A_2 = 15.63 \times 15 = 234.45$

For 5"/38 gun $A_3 = 5.87 \times 10 = 58.7$

Figure 7. Gun Effectiveness

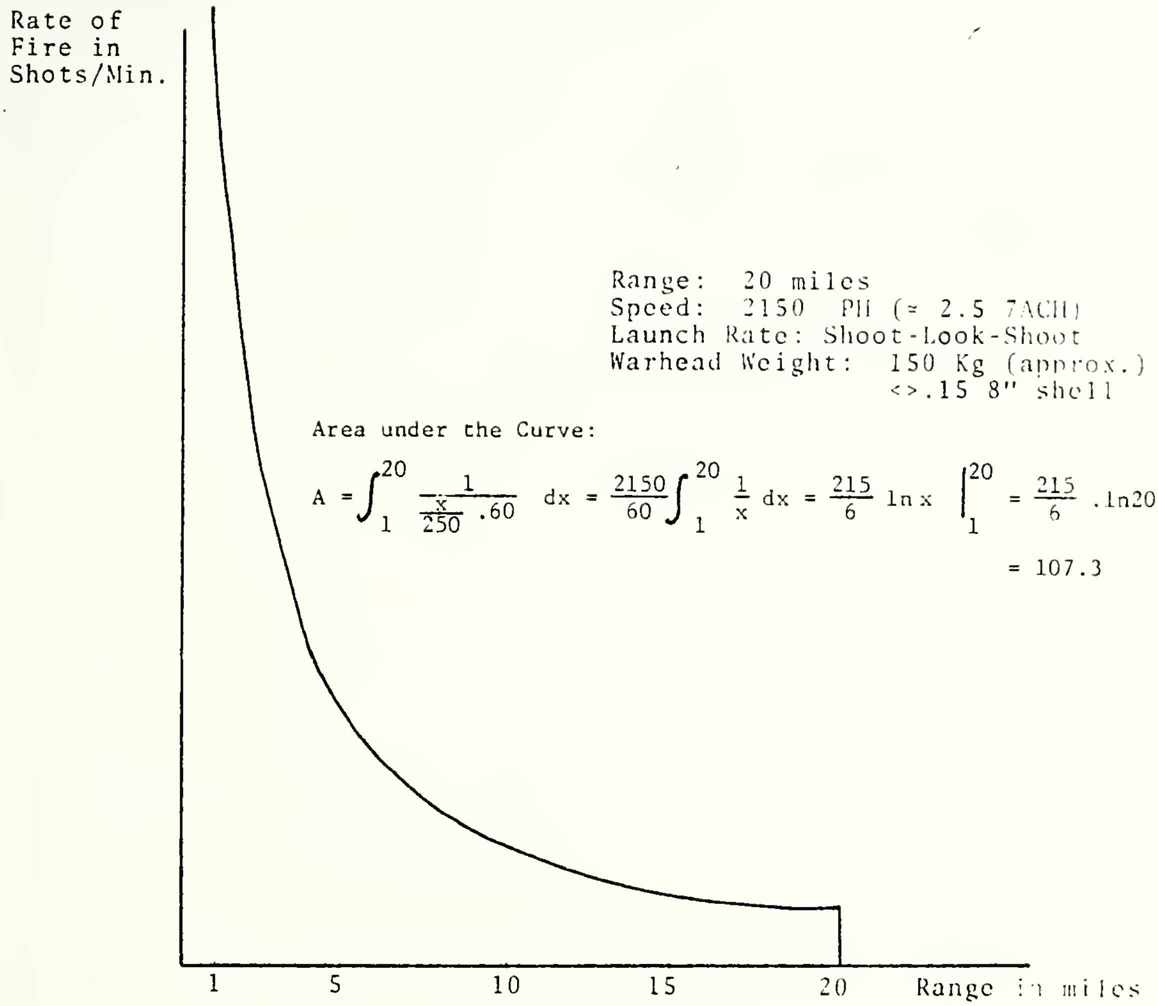


Figure 8. Terrier

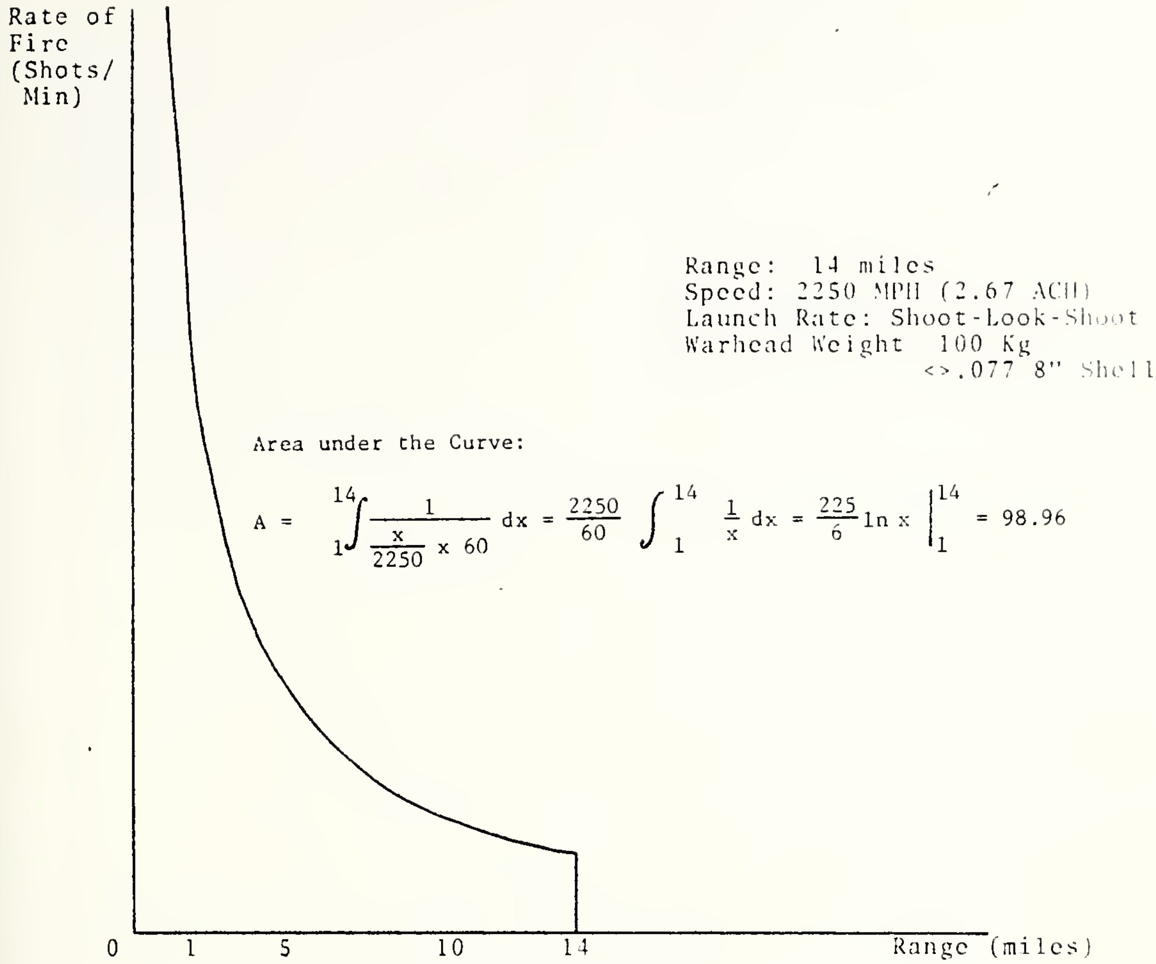


Figure 9. Tartar

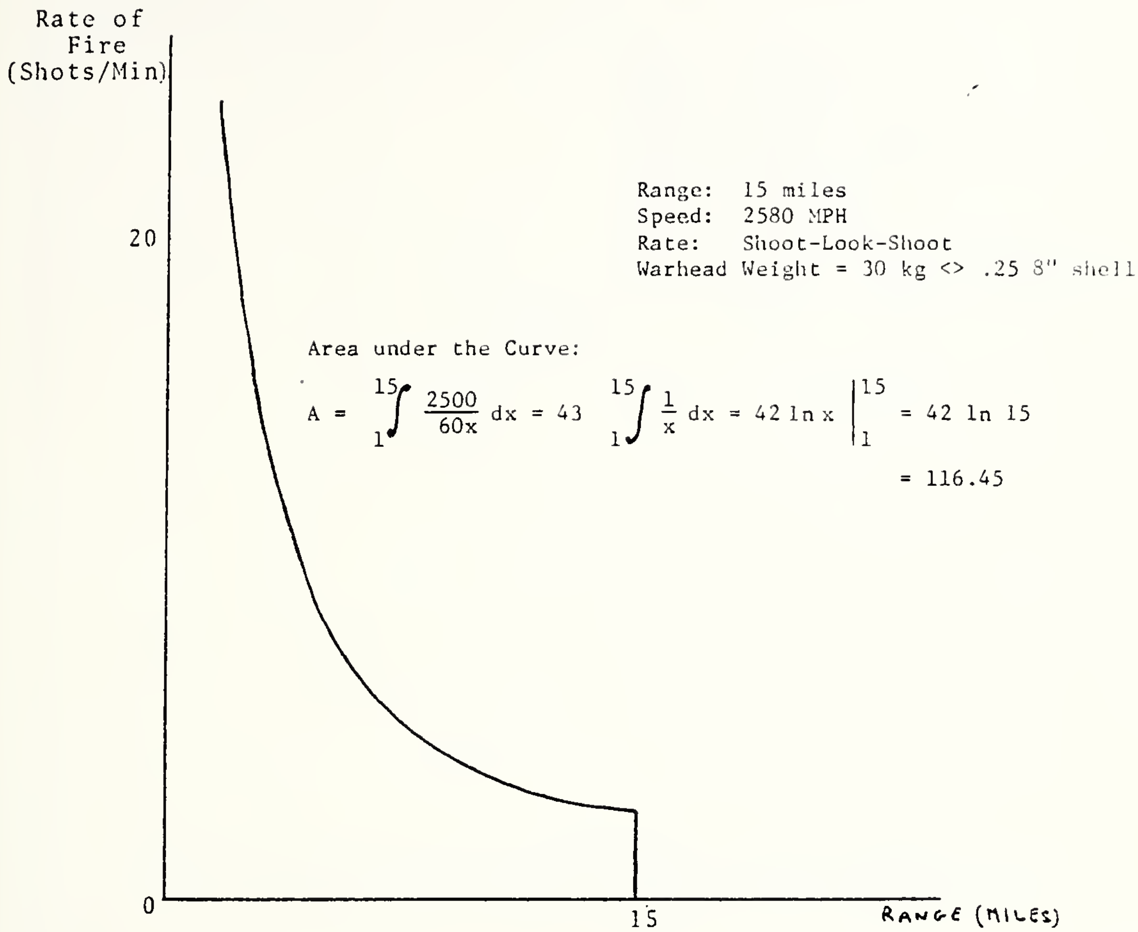


Figure 10. Sea Sparrow

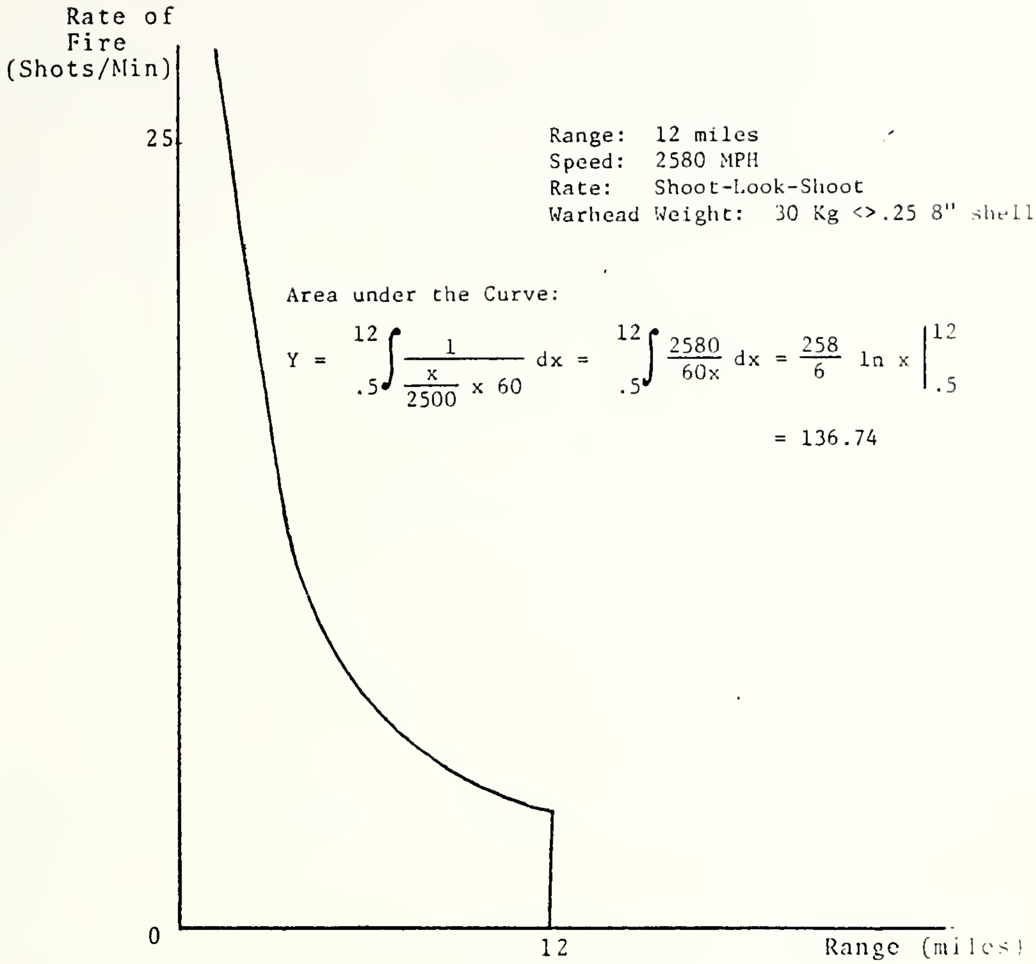


Figure 11. NATO Sea Sparrow

Table XIV. Effectiveness for Guns

	Index	Number of Ships	Types of Guns	Gun Eff. Per Ship	Force Ship Effect.
1. DE 1006	16.2	139	4 x 3"/50	67.52	9385.3
2. DE 1037	71.4	88	3 x 3"/50	50.64	4456.3
3. DE 1040	90.8	102	2 x 5"/38	117.4	11974.8
4. DEG 1	152.8	80	1 x 5"/38	58.7	4696.0
5. DD 931	70.3	110	4 x 3"/50 3 x 5"/54	710.87	84795.1
6. DDG 2	168	74	2 x 5"/54	468.9	34698.6
7. DLG 6	217.1	54	1 x 5"/54	234.45	12660.3
8. DLG 16	253.6	47	4 x 3"/50	67.52	3173.4
9. DLG 26	259.4	48	2 x 3"/50	273.21	13114.1
10. DE 1052	140.8	84	1 x 5"/54	234.45	18693.8
11. DD 963	216.5	55	2 x 5"/54	468.9	25189.5

Table XV. Missile Effectiveness Evaluation

Missile Name	Range	Warhead Weight	Equiv. Number of 8" Shells	Area Under Curve	Prod. AxB
NATO (Sea Sparrow) BDPNS	12	30	.25	136.7	34.18
TERRIER	20	150	1.15	107.34	123.44
TARTAR	14	100	.85	98.96	84.12
SEA SPARROW (DG 963)	15	30	.25	116.45	29.11
HARPOON	30	200 (a)	1.33	121.8	162.03

(a) estimated

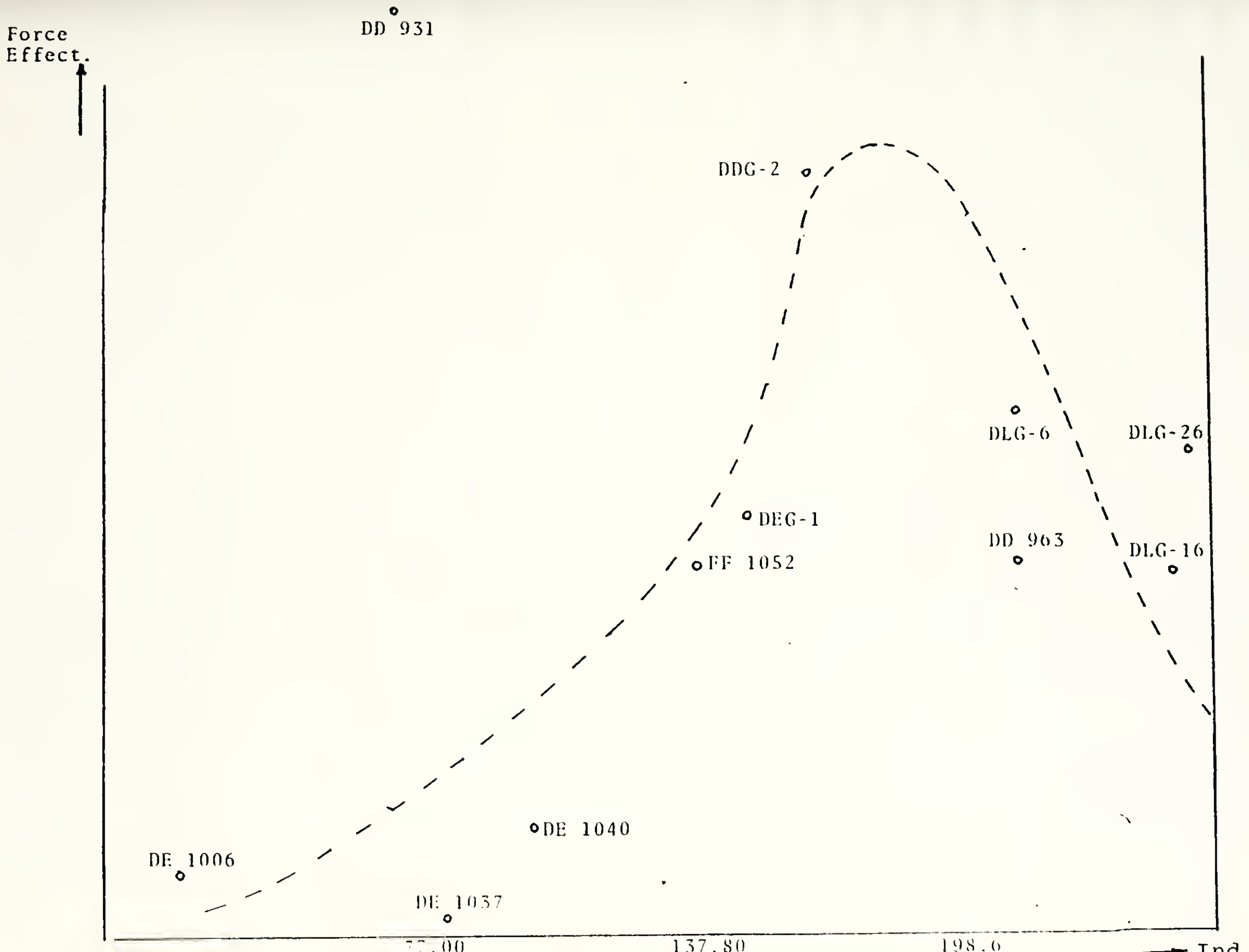


Figure 12. AA and Missile Effectiveness

The weight of explosive in the warhead is converted in the equivalent number of 8" shells by dividing by the weight of an 8" shell (117 kg). The choice between E8R and AFP is questionable. It is obvious that AFP is the measure of effectiveness to use when the position of the target is known, when there is feedback about firing errors and also when the dimensions of the target must be taken into account. E8R is better whenever blast sensitive targets are being considered, as well as in circumstances not agreeing with the area fire assumptions. According to A. Washburn,[12] it has been used as the basic measure of effectiveness and will be used exclusively in this study.

5. Computation of Joint AA and Surface Index

a. Guns

Once the measures of effectiveness for each gun have been computed, (given by the areas under the curves), we must multiply these values by the number of guns of each type existent aboard the ship and then by the number of ships in the force to obtain its total effectiveness. Table 15 shows these computations.

b. Missiles

For each type of missile, the equivalent number of 8" shells (obtained as above by dividing the warhead weight of explosive by the weight of explosive in an 8" shell), is multiplied by the area under the curve representing range

vs rate of fire and the missile effectiveness thus obtained (See Table XVI.). Multiplying now by the number of ships in the force, the total force effectiveness is obtained.

c. Joint Gun and Missile Effectiveness Index

To account for the precision of missile fire, the missile total force effectiveness is multiplied by a factor of five before being added up to give the gun force effectiveness. Had this not been done, there would result an unbalance in favor of the gun effectiveness. It would, however, not seriously affect the final results.

6. Combined ASW/AA/Surface Effectiveness

The ASW and the Fun and Missile (G&M) measures of effectiveness are scaled by dividing by 6000 to get reasonably low numbers and combined by obtaining their mutual product. These values are shown in Table XVII and plotted in Figure 13. Figure 13 shows the total combined design-to-cost model.

E. COMMENTS

From the graph a few conclusions can be taken:

(1) The maximum can be estimated to occur somewhere between an index of 140 and 170, most likely close to the value obtained for the DDG 1, that is, an index of 160. This corresponds to a cost for the first unit of \$49 Mi and an average price of \$37.5 Mi in 1970 dollars (about \$43 Mi in 1973), for a total of 80 ships, considering again a learning scope of 94.6%.

(2) The two classes of ships that do not fit the curve drawn are the DLG 26 and the DD 963. In regard to the former we are convinced that the performance index as computed by ESCOMO was overcalculated. The ASROC/TERRIER double purpose launcher is counted twice which does not seem to be correct. Once this error was corrected a value closer to the curve would be obtained. In regard to the DD 963, a higher value for the cost would give a point closer to the curve.

(3) It should also be noted that the DEG 1 and the FF 1052 have reversed positions in what concerns index and displacement. The DEG 1 has an index of 152.8 and a displacement of 3500 while the FF 1052 has an index of 140.8 and a displacement of 3950. As the differences both in index and displacement are not excessive, this fact will not affect significantly the conclusions.

(4) According to the plot the displacement correspondent to the adopted maximum of the curve will be in the order of the 3500 tons, possibly a little higher.

F. SENSITIVITY ANALYSIS

The calculations were repeated for a budget of $2 Bi to check for the constancy or variability of the solution for a different budget. The results are displayed on Tables XVIII, XIX and XX and the correspondent graphs on Figures 15 (only ASW), 16 and 17 (combined AA/surface and ASW).

Analyzing the graphs it can be examined that the results are similar to those found for the higher budget of $3 Bi.

From the combined graph (Figure 18) we have a maximum for an index of about 160, which corresponds to a cost for the first unit of $49 Mi and an average cost of $40 Mi in 1970 dollars ($45.8 in 1973), and to a force of 52 ships. A learning slope of 94.6% was again used.

G. SUMMARY

In this chapter a curve relating force effectiveness and performance index was drawn. The procedure involved the definition of MOE's for ASW and AA/Surface capabilities of each force. For ASW and MOE concerning the area covered by the force was computed and corrected for the ASW weapon available. For AA/Surface, the "weight of broadside" considering typical rates-of-fire for guns and a shoot-look-shoot rate for missiles was used. The two MOE's were generally combined to get a single value which would characterize overall force effectiveness. This was plotted against performance index and the curve representing the third linear relationship thus obtained.

Table XVI. Computation of Ordnance Effectiveness Index

	Index	Number of Ships	Missile	Missile MOE	Missile Total Effect.	Missile x5	Gun F.E.	Total	Scaling ÷6000
1. DE 1006	16.2	139	None	--	--	--	9385	9385	1.56
2. DE 1037	81.4	88	None	--	--	--	4456	4456	.76
3. DE 1040	100.8	102	None	--	--	--	11975	11.975	2.00
4. DEG 1	152.8	80	TARTAR	84.12	6729.6	33648.0	4696.0	38344.	6.39
5. DD 931	70.3	110	None	--	--	--	84796.0	84796.0	14.13
6. DDG 2	168.0	74	TARTAR	84.12	6224.9	31124.5	34699.	65823.5	10.97
7. DLG 6	217.1	54	TERRIER	123.44	6665.8	33329.0	12660.3	45989.3	7.66
8. DLG 16	253.6	47	TERRIER	123.44	5801.7	19008.5	3173.4	32181.9	5.36
9. DLG 26	259.4	48	TERRIER	123.44	5925.1	29625.5	13114.0	42739.5	7.12
10. DE 1052	140.8	84	SPARROW (IPDMS)	34.18	2871.1	14355.5	19694.8	34050.3	5.68
11. DD 963	216.5	55	SEA SPARROW	29.11	1601.1	8005.5	25790	33795.5	5.63

Table XVII. Combined ASW, G&M Effectiveness

	Index	# of Ships	Gun & Missile Comb. Index	ASW Index	Product
1. DE 1006	16.2	139	1.56	1.43	2.23
2. DE 1037	71.4	88	.74	4.59	3.40
3. DE 1040	90.8	102	2.00	7.51	15.02
4. DEG 1	152.8	80	6.39	5.16	32.97
5. DD 931	70.3	110	14.13	.76	10.74
6. DDG 2	168.0	74	10.97	1.63	17.88
7. DLG 6	217.1	54	7.66	.87	6.66
8. DLG 16	253.6	47	5.36	.66	3.54
9. DLG 26	259.4	48	7.12	1.44	10.25
10. DE 1052	140.8	84	5.68	4.79	27.21
11. DD 963	216.5	55	5.63	2.89	16.27

Table XVIII. Force Effectiveness for Costs Non-Adj. and Adj. for Speed
(Budget = $2 Bi)

	Non-Adj. Cost	Max. Speed	Number of Ships	Perf. Index	Prod.	Diff. for 30 KN	Diff. in Cost	Adj. Cost	Number of Ships	Total Effect
1. DE 1006	16.0	27.2	125	16.2	2025	(+)2.8	5.68	21.68	92	1494
2. DE 1037	25.9	26.0	77	71.4	6286	(+)4.0	8.12	34.02	59	4785
3. DE 1040	25.5	28.0	78	90.8	7906	(+)2.0	4.06	29.34	68	6871
4. DEG 1	33.5	28.0	60	152.8	9122	(+)2.0	4.06	37.56	53	8136
5. DD 931	36.96	34.8	54	70.3	3804	(-)4.8	9.74	27.22	73	5165
6. DDG 2	48.5	34	41	168	6928	(-)4.0	8.12	40.38	50	8321
7. DLG 6	64.5	34.5	31	217.1	6734	(-)4.5	9.14	55.36	36	7844
8. DLG 16	69.5	32.5	29	253.6	7298	(-)2.5	5.08	64.42	31	7874
9. DLG 26	68.0	33.0	29	259.4	7629	(-)3.0	6.09	61.91	32	8373
10. FF 1052	21.5	28.0	63	140.8	8940	(+)2.0	4.06	35.84	56	7857
11. DD 963	54.0	30	37	216.5	8019	0.0	0.0	54	37	8019
Only Missile Ships Mean: 7810 St. Dev: 937.4						Only Missile Ships Mean: 8060 St. Dev: 222.1 (reduced 23%)				

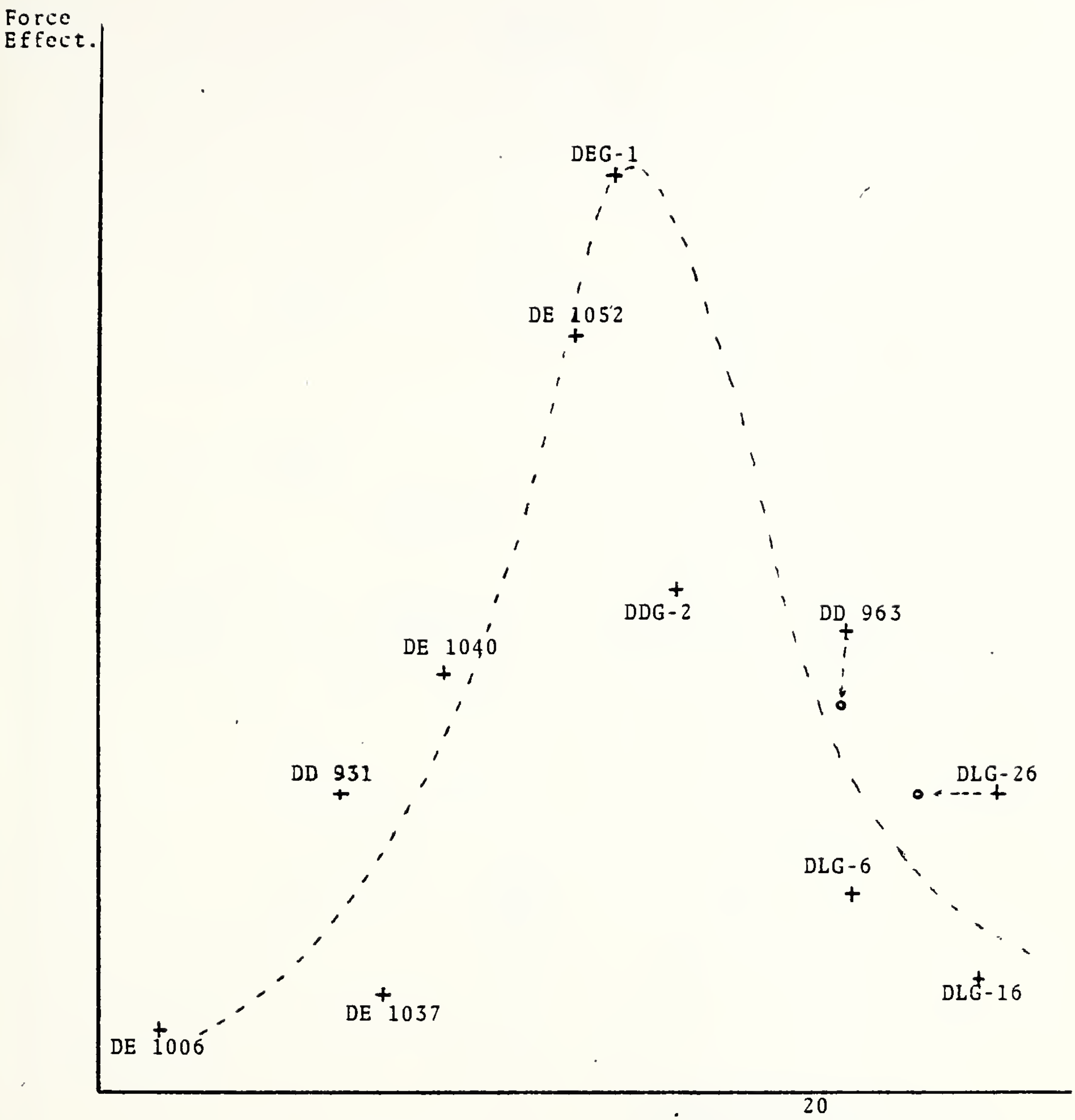


Figure 13. Combined ASW, AA & Surface Effectiveness vs Perf. Index

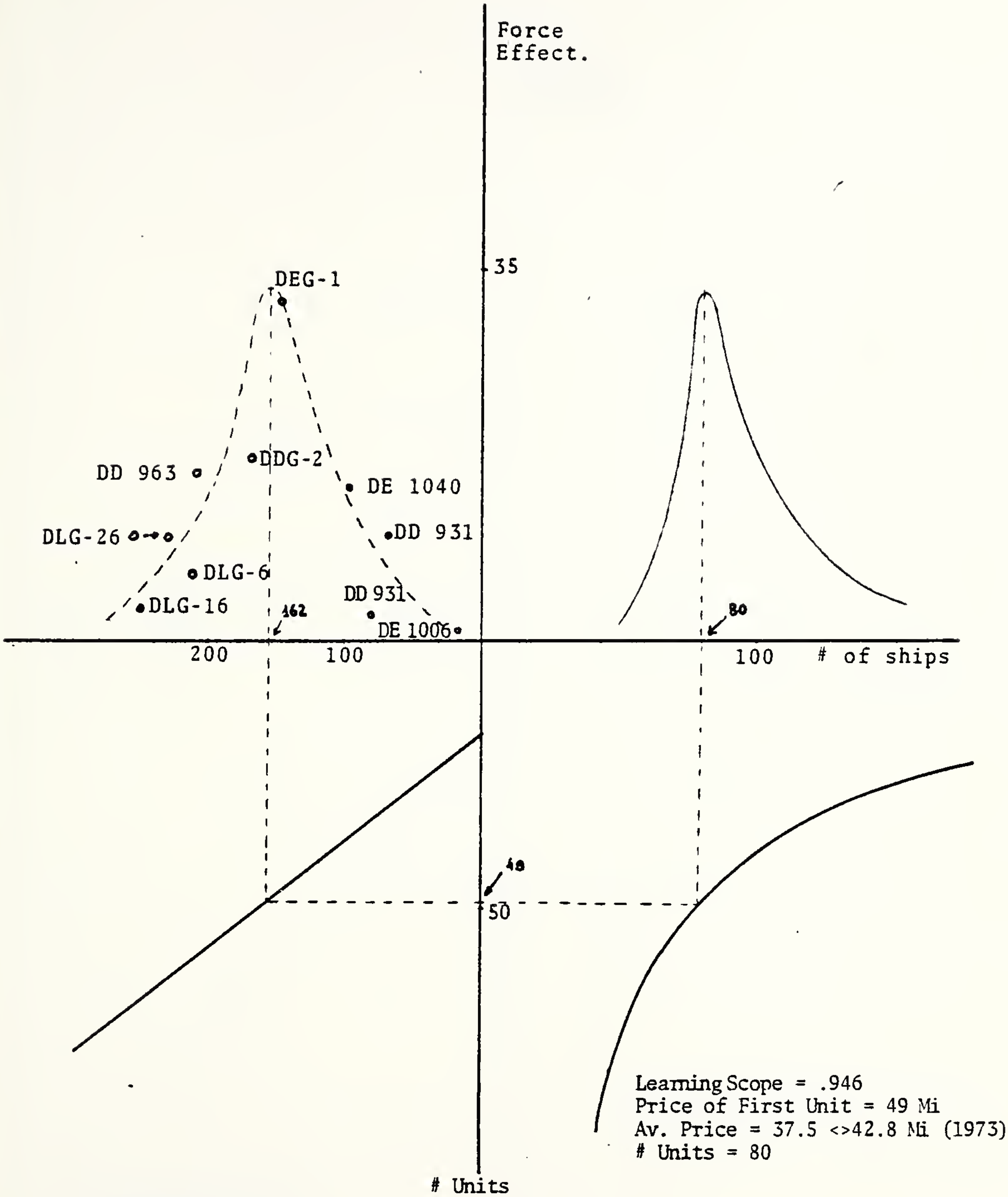
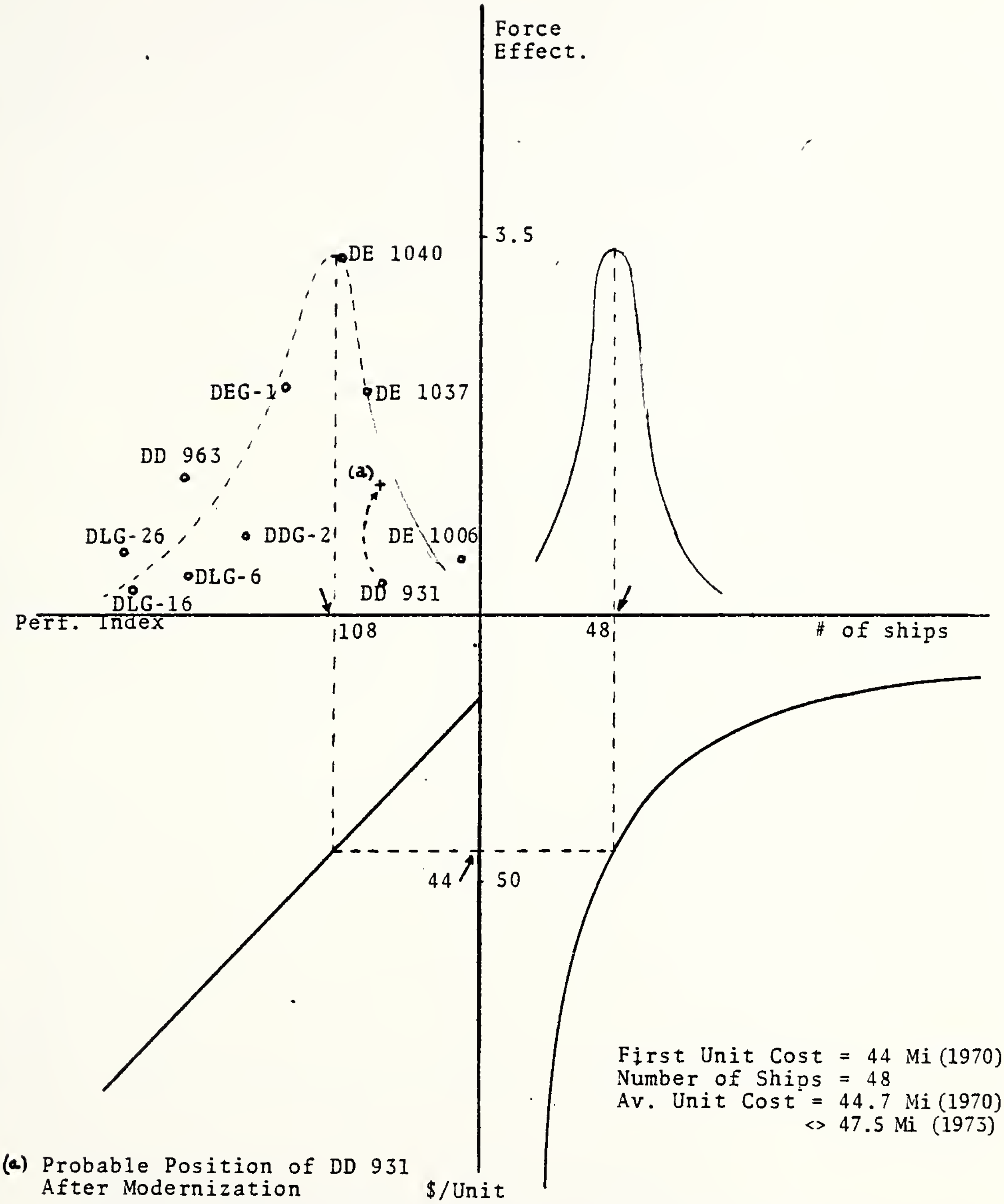


Figure 14. Combined Design-to-Cost Model (ASW, AA, Surface) .
For a Budget of $3 Bi



(a) Probable Position of DD 931
After Modernization

Figure 15. Combined Design-to-Cost Model for Budget = $2 Bi
(only ASW warfare)

Table XIX. Computation of Sonar Index for Budget = $2 Bi

	Number of Ships (After Adj.)	Product X Eff. Range	$R = \frac{\text{Prod.}}{2\pi}$	Index (R÷50) -A-	ASW Weapons Weight	Prod. By Number of Ships	ASW Weapon Scaled -B-	ASW Index (AXB)
1. DE 1006	92	276	43.95	.83	40	3680	.616	.540
2. DE 1037	59	472	75.16	1.50	140	8260	1.377	2.06
3. DE 1040	68	544	86.62	1.73	170	11560	1.93	3.34
4. DEG 1	53	424	67.52	1.35	190	10070	1.68	2.27
5. DD 931	73	219	34.87	.70	40	2920	.49	.34
6. DDG 2	50	200	31.85	.64	140	7000	1.17	.74
7. DLG 6	36	144	22.93	.46	140	1040	.84	.39
8. DLG 16	31	124	19.75	.40	140	4340	.72	.29
9. DLG 26	32	288	45.86	.92	130	4160	.69	.64
10. DE 1052	56	448	71.34	1.43	160	1960	1.49	2.13
11. DD 963	37	370	58.92	1.18	180	6660	1.11	1.31

Table XX. Computation of Combined G&M and ASW Effectiveness

	Index	# of Ships	Missile M.O.E.	Missile Force Eff.	Missile Eff. X5	Gun F.E.	Total G&M Eff.	Scaling ÷6000	ASW Ind.	Total Effect
1. DE 1006	16.2	92	--	--	--	6211.8	6211.8	1.03	.54	.56
2. DE 1037	71.4	59	--	--	--	2987.8	2987.8	.50	2.06	1.03
3. DE 1040	90.8	68	--	--	--	7983.2	7983.2	1.33	3.34	4.44
4. DEG 1	152.8	53	84.12	4458.13	22291.8	3111.1	25402.9	4.23	2.27	9.60
5. DD 931	70.3	73	--	--	--	56273.5	56273.5	9.38	.34	3.19
6. DDG 2	168.0	50	84.12	4206.00	21030.	23445.	44475.	7.44	.74	5.48
7. DLG 6	217.1	36	123.44	4443.84	22219.2	8440.2	30659.4	5.11	.39	1.99
8. DLG 16	253.6	31	123.44	3826.64	19133.2	2093.1	21226.3	3.54	.29	1.03
9. DLG 26	259.4	32	123.44	3950.08	19750.4	8742.7	28493.1	4.75	.64	3.04
10. DE 1052	140.8	56	34.18	1914.08	9570.4	13129.2	22699.6	3.78	2.13	8.05
11. DD 963	216.5	37	23.11	1077.07	5385.4	17349.3	22734.7	3.79	1.31	4.96

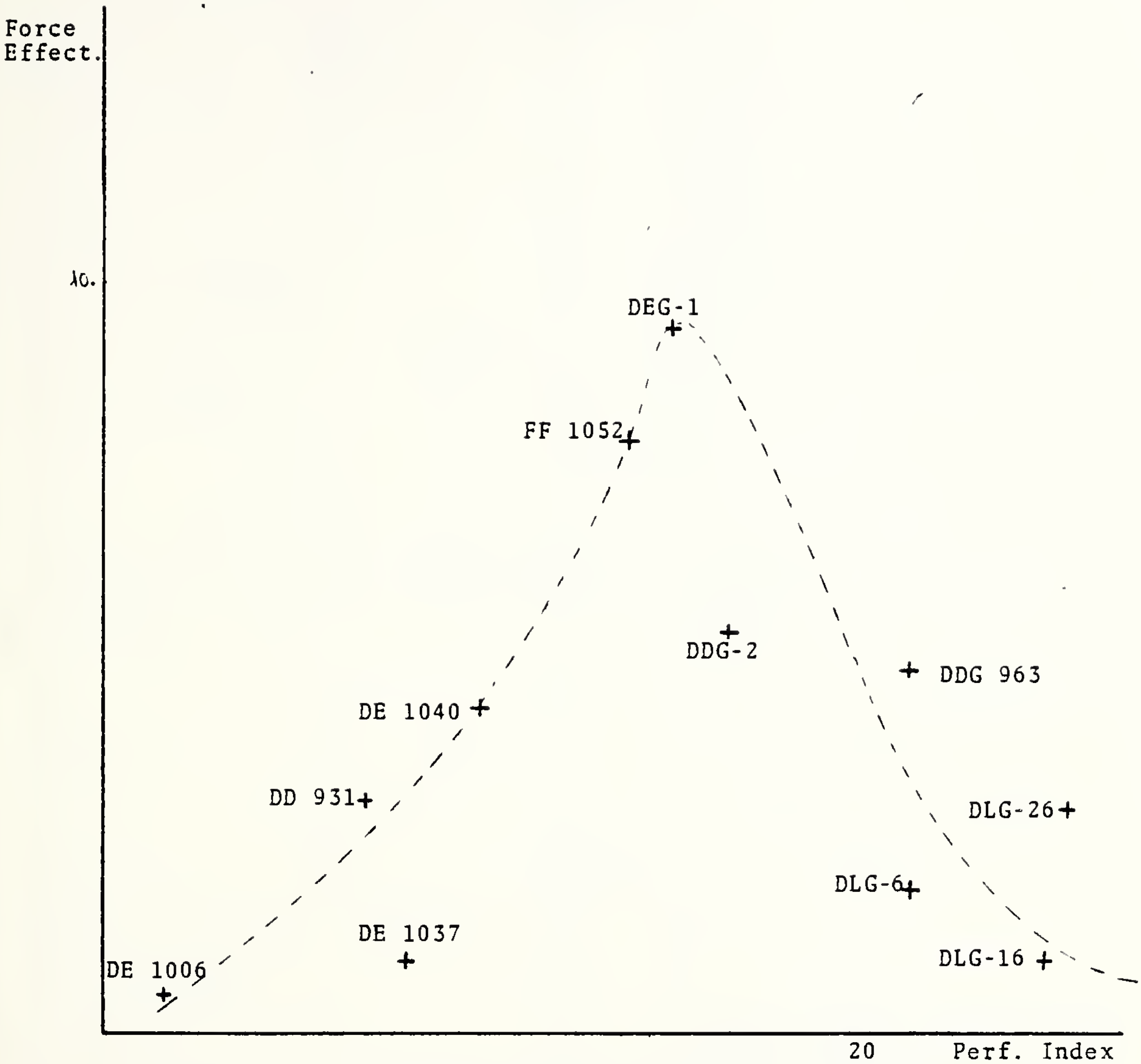


Figure 16. Force Effectiveness vs Perf. Index For Budget =\$2 Bi (ASW, AA, and Surface)

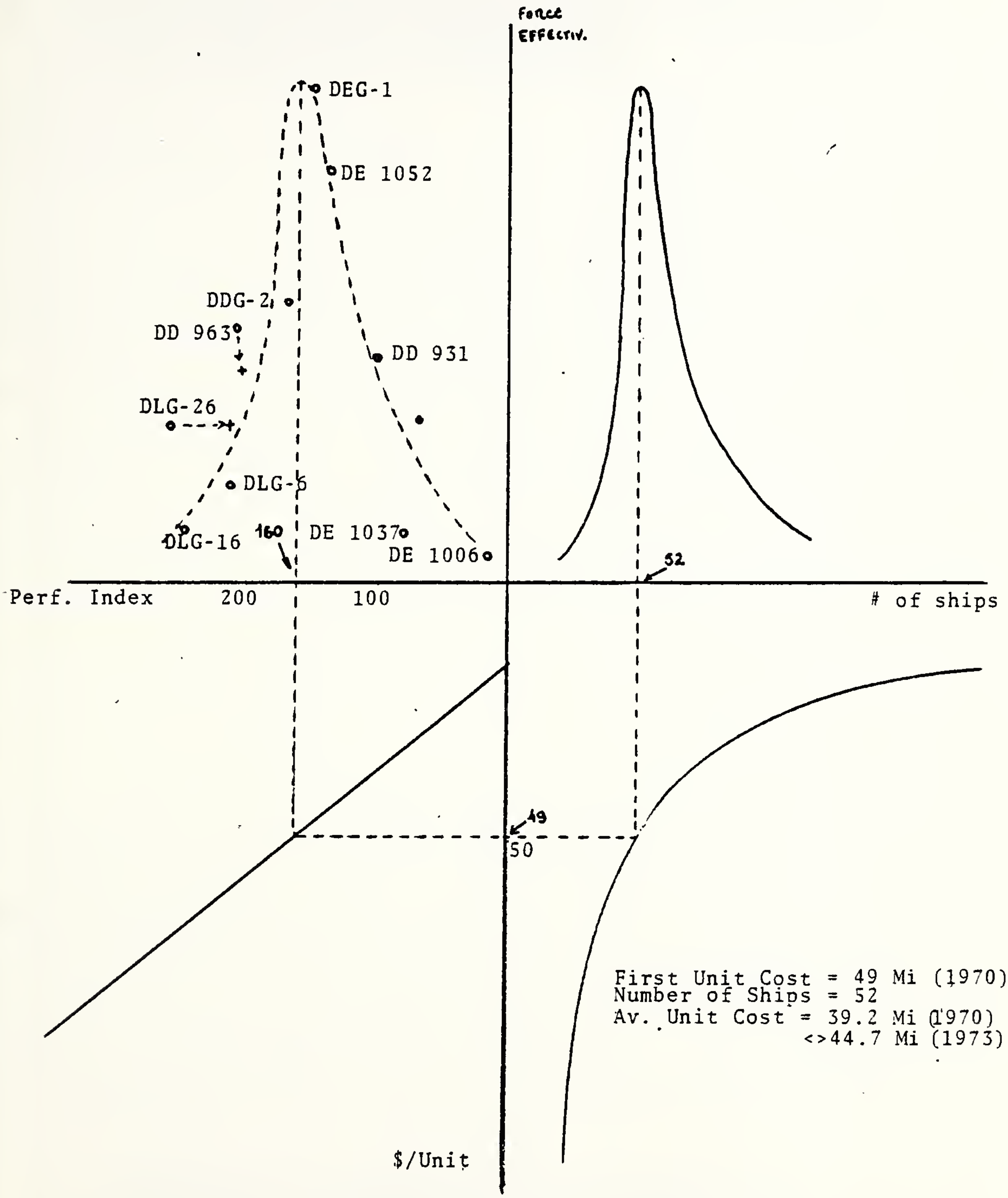


Figure 17. Combined Model for ASW, AA and Surface for Budget = $2 Bi

VI. ANALYSIS OF VARIANCE, VERIFICATION OF THE SOLUTION, FINAL COMMENTS AND RECOMMENDATIONS

A. INTRODUCTION

The full model is now complete. From the third basic relationship the performance index, which maximizes the effectiveness of the force, is obtained. From the first basic relationship the cost of the first unit for that index is obtained. Finally, the second basic relationship will give the number of ships in the force and, with a certain approximation, their displacement. Let us now proceed to some considerations concerning uncertainty in this model.

B. ANALYSIS OF VARIANCE

In order to obtain a reasonable interval within which the solution could be found with high probability, three types of uncertainty must be considered: in the slope of the learning curve, in the CER (second basic relationship), and also in the definition of the maximum of the curve representing the force effectiveness relationship. Let us start with the first.

1. Uncertainty in the Slope of the Learning Curve

We have adopted the most likely value of 94.6% for the slope of the learning curve. The limits for a 95% confidence

interval can be easily established using the expression:

$S \pm t_c \cdot s_\beta$ where t_c is the t value computed for N-2 degrees of freedom, being N the number of observations. As we have seven observations, we have five degrees of freedom, and hence a t_c of 2.30.

For the known standard deviation of .717 (See Table VII) we have:

Max $94.6 + 2.30 \times .717 = 96.25$

Min $94.6 - 2.30 \times .717 = 92.95$

Consequently using the expressions given in "Military Equipment Cost Analysis," Chapter 6[13] we get:

Most likely slope	$S = 94.6\%$	$b = -0.08$
Lowest probable slope	$S = 92.95\%$	$b = -0.105$
Highest probable slope	$S = 96.25\%$	$b = -0.06$
Expected slope	$\bar{S} = \dfrac{S_L + 4\ S + S_H}{6}$	
Standard deviation	$\delta_s = \dfrac{96.25 - 92.95}{3} = \dfrac{3.30}{3} = 1.10$	

2. <u>Uncertainty on the CER</u>

The CER gives us a linear relationship of the type

$COST = \beta_0 + \beta_1 \times (INDEX)$ where $\beta_0 = 17.4$ and $\beta_1 = 0.1949$.

From the variance - covariance matrix given in the computer output for costs adjusted for speed, we have $\sigma_{\beta_0} = 6.97$ and $\sigma_{\beta_1} = 2.40 \times 10^{-4}$, thus $s_{\beta_0} = 2.64$ and $s_{\beta_1} = 0.015$. The values for β_0 will then be with a probability of .95 within the limits

$$\beta_0 \pm t_c \cdot s_{\beta_0} = 17.4 \pm 2.26 \times 2.64 = 17.4 \pm 5.96$$

$$= (11.44,\ 23.36)$$

For $\beta_1 \pm t_c \cdot s_{\beta_1} = 0.1949 \pm 0.034 = (0.161,\ 0.229)$

The value of $t_c = 2.26$ was used because we now have nine degrees of freedom, correspondent to the eleven observations, that is, the eleven types of ships being considered.

3. Uncertainty on the Definition of the Maximum in the Curve Representative of the Effectiveness of the Force

Let us observe the combined graph for a budget of \$3 Bi given in Figure 14. The curve must peak for a value of the index performance somewhere between the 168 of the DDG 2 and the 140 of the FF 1052. In between we have the maximum value computed, 152 relative to the DDG 1. We can consider as reasonable limits for the interval containing the maximum 150 and 170. These same limits would be used for the case where the budget is \$2 Bi.

4. Conclusions

Figure 18 shows the lower and the upper limits for both the CER and the learning curve. Considering the most unlikely case of all the extremes occurring simultaneously, we would get a value for the lower cost of \$35 Mi and upper cost of \$63 Mi with a correspondent number of ships of 126 and 58, and displacements of about 3000 and 4200 tons, respectively.

Again the expected values would be:

$$\text{Expected cost} = \frac{35 + 4 \times 49 + 63}{6} = 49$$

$$\text{Expected number of ships} = \frac{58 + 4 \times 80 + 126}{6} = 80$$

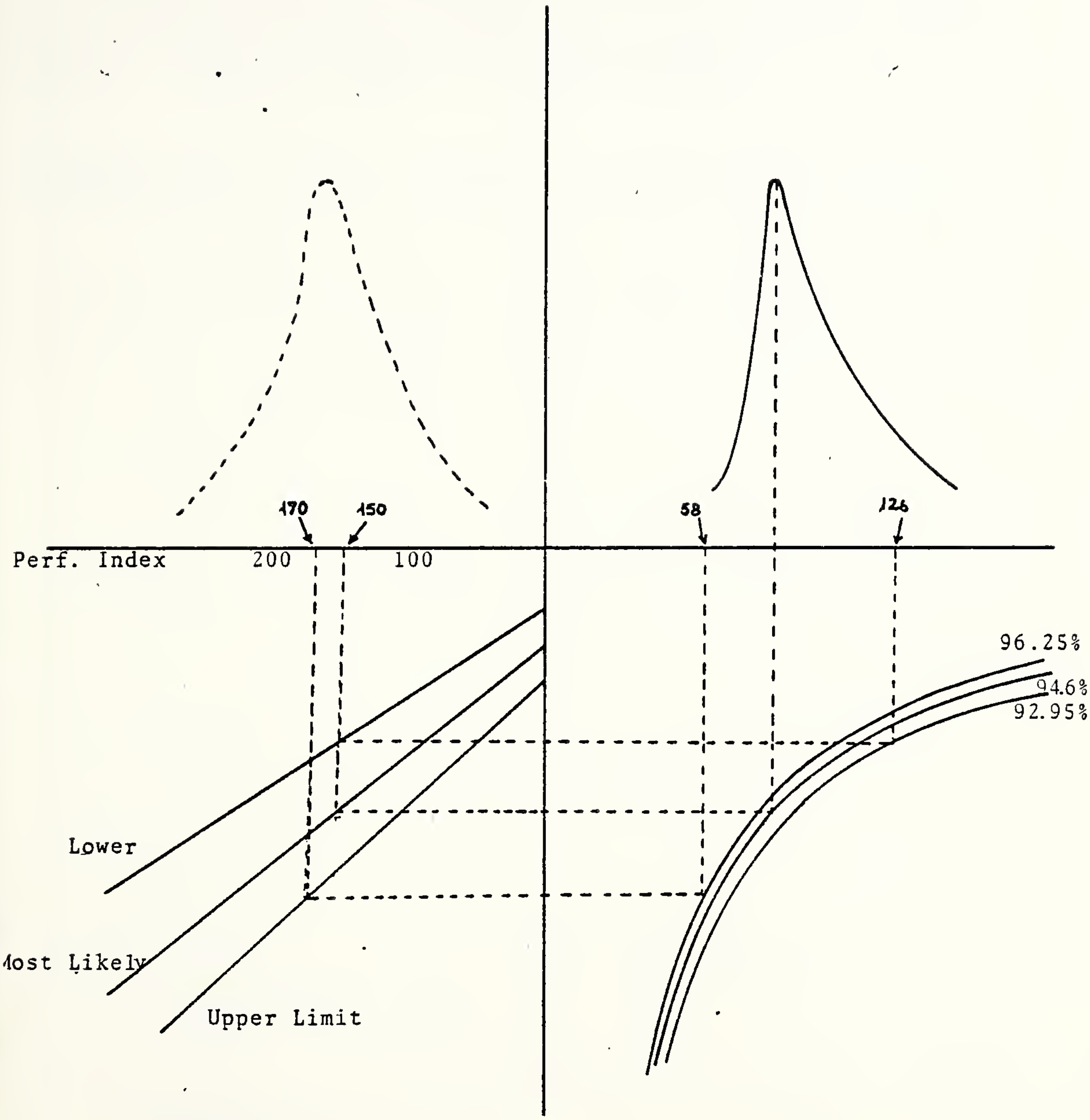


Figure 18. Uncertainty on the Combined Design-to-Cost Model for a Budget of $3 Bi

If we restrict ourselves to the limits of the performance index 150 and 170, disregarding the learning and CER uncertainties, the number of ships would be in the interval (74, 82) with the correspondent first unit costs of $47.5 and $52 Mi. There would be no evident change in the displacement.

C. VERIFICATION OF THE SOLUTION BY COMPARING TO THE REAL FFG-7

Let us now verify how the FFG-7, as the ship was built, fits into the solution shown by the graphs of the preceding sections.

We start by computing the indices:

<u>SONAR INDEX</u>

Max range of the SQS 56 = 30 miles

Frequency = 4.5 khz

Quotient r/f = 30/4.5 = 6.67

Index = Quotient x 2 = 13.3

<u>GUN INDEX</u>

MK 75 OTO MELARA = 76 mm <> 2.99 in.

Rate of fire 85 rpm

Range 9 n.m.

Gun index = 9.0 x (1 + 1.5) x 2.99 = 67.28

Gun index ÷ 5 = 13.46

<u>SMS INDEX</u>

HARPOON/STANDARD MISSILE RANGE = 30 miles for Harpoon

= 20 miles for Standard

One FC system for both the missiles and the 76/62 gun

MK 92 Mod 2 - weighted as 2.5

$30 \times (1 + 1 + 2.5 + 1) = 165$ (110 for the Standard)

TOTAL PERFORMANCE INDEX

SONAR x 2 + GUN/5 + SMS + HELO = 13.3 + 13.46 + 165 + 10
= 201.76

(146.76 for standard missile)

Using the performance index to compute the price of the first unit we would find:

COST = -56.13 + 0.1949.(201.76) + 2.4511 x 29.5 = $55.5 Mi

or, using the expression adjusted for speed

COST = 17.403 + 0.195 x (201.76) = $56.74 Mi

D. FINAL COMMENTS

1. The cost for the FFG-7 as given by the CER is well above the one given by the graph: $56.7 Mi vs $49 Mi. This is due basically to the fact that the cost of $49 Mi corresponds to a performance index of 160, while the index computed for the FFG is 201 if we consider a range of 30 for the Harpoon, but is only 147 taking 20 as the range for the Standard Missile. The range of 22 would give us a total index of 165, very close to the 160 that corresponds to the most likely peak of the curve.

2. It is not easy to determine the exact displacement that corresponds to a certain number of ships. That stems from the fact that there does not exist a linear relationship between performance indices and displacement, that is, a larger ship does not necessarily perform better. This is specially relevant when we compare old ships with new ones equipped with more

updated and sophisticated weapons. Sometimes shifts between performance indices and displacement occur like the one with the FF 1052 and the FFG 1. This fact could possibly been avoided if a different criterion for computation of the performance index had been adopted. However, it was decided to follow the methodology indicated by ESCOMO as the correlation between the indices calculated following that model and costs were very high. Besides, there existed no guarantee that some improvement would be obtained regarding the achievement of a better definition of the displacement.

3. In a very general way it can be said that the ships for which the plotted points, representing force effectiveness, lie in the interior of the curves (Figures 13 and 16) that were tentatively drawn through all points, have capabilities inferior to those that would be expected from a ship with its characteristics, like displacement, speed, etc.... This can be said about the DE 1037, DDG-2, DLG-6 and DLG-16. On the other hand, ships for which the plotted points lie outside the curve can be considered as better than could be expected, that is, having improved their performance relatively to the previously existent ships. This could apply to the DLG-26, DD 963 and also the FFG-7.

The fact that some characteristics of the Harpoon and Standard Missile were not available did not allow carrying out the computation of the equivalent E8R and thus of the G&M force effectiveness. Assuming a warhead weight slightly above 200 kg and a speed of 2.5 Mach, the final measure of effectiveness

would be about 35, after having been scaled. That would place the plotted point practically on the peak of the graph, if we had assumed a performance index of 160. If we take a larger number for index, then the plotted point would be well outside the curve, which would prove the superior capabilities of this ship (See Figure 15). Some additional weapons that are supposed to be installed soon, like the CIWS, the passive towed array sonar and the LAMPS III helos will certainly improve this already remarkable ship.

E. RECOMMENDATIONS

In face of the reasonable and convincing results obtained in this study, which are very similar to those presented by Vice Admiral Price in his congressional testimony, and of the fact that this was achieved in spite of the scarcity of information and of the simple, straightforward methods used, it is recommended that similar studies following this general outline should be encouraged whenever a shipbuilding program is to take place. Such a study is not certainly expected to give precise final results or conclusions. This is a type of study that must be conducted during the early phases of planning when the characteristics of the new ship are being discussed and tradeoffs between alternate ship configurations are being considered. These tradeoffs can be more easily visualized with the use of models and their graphs like those used previously in this study.

Further study and developments should be conducted using accurate data especially aimed at:

(1) Finding good models for AA, ASW and Surface Warfares. Mathematical models, specially conceived and taking into account tactical considerations would be most useful.

(2) Finding alternate ways of computation for the performance indicates that would offer a better relationship with displacement and other characteristics.

(3) Finding a way to include maintenance and support costs that is life cycle cost in the model, instead of just procurement costs.

It is important also to suggest that with the availability of new data resultant from new building programs being completed, this new element should be added to the model and old ones removed. That enables to keep the model updated and restricted to ships with similar characteristics.

APPENDIX A

THE ESCOMO MODEL

1. General Description

ESCOMO is a statistically derived model produced at the Center for Naval Analysis used to estimate end costs of new escort ships. The purpose of this model is to relate costs to performance characteristics of a ship substituting for the more traditional method of having costs related to physical characteristics like weight, shape, etc.... The former procedure made quite difficult and sometimes even impossible to analyze and understand how performance affects costs and how these costs can in turn be related to desired benefits.

Research was then undertaken to derive statistical cost estimating relationships (CER's) between the end costs and the performance characteristics of escorts. Production characteristics were also included in the model, like quantities of ships built, number of builders and the dates in which the ships were built.

The analysis that were undertaken were divided in two parts, a primary analysis deriving CER's that were only based on explanatory variables that describe escort ship performance and production characteristics, and a secondary analysis in which CER's include full load displacement as an explanatory variable. Nuclear powered escorts were also included in some of the models of the secondary analysis.

2. Results of Primary Analysis

After analyzing 100 conventionally powered escorts, the following equation was established:

$$(1)\quad LADJ\$ = -0.9778 + \underset{(12.8)}{0.088MAXSP} + \underset{(3.22)}{0.57\ LCRWF}$$

$$+ \underset{(3.84)}{0.09\ LSONR} + \underset{(5.27)}{0.0025\ ORD} - \underset{(-4.32)}{0.102LSQYD}$$

where:

LADJ\$ = ln of end costs adjusted to 1970 Mi of dollars

MAXSP = maximum speed in knots

LCRWF = ln of crew factor (quotient of full load displacement by crew accommodations)

LSONR = ln of Sonar index

ORD = ordnance index (G&M)

LSQYD = ln of building sequence number by class within the same shipyard

The numbers in parentheses below the coefficients are the t-statistics of those coefficients.

F-statistics = 266.2

Multiple correlation coefficient (R^2) = 0.934

Standard error of the estimate = 0.13

Durbin-Watson statistic = 2.00

The values of t and F statistics and Durbin-Watson show significance at the 95% level of confidence, and the absence of serial correlation in the residuals. The hypothesis that end costs are related to certain variables describing performance and production characteristics in escort ships is accepted.

Applying logarithms to the equation (1) we get:

$$\exp \text{LADJ\$} = 0.376\ e^{0.088\text{MAXSP}}\ .\text{CRWF}^{0.57554}\ .\text{SONAR}^{0.09}$$
$$\times\ .e^{0.0025\ \text{ORD}}\ .\text{SQYD}^{-0.012}$$

where

exp LADJ$ = antilogarithm of LADJ$

0.376 = antilogarithm of -0.97778

MAXSP = max speed in knots

CRWF = crew factor

SONAR = Sonar index

ORD = Ordnance (gun and missile) index

SQYD = building sequence by shipyard and class

As the distribution of exp LADJ is lognormal, it does not estimate the mean of the distribution of exp LADJ$. Therefore, it must be multiplied by a corrective factor to eliminate the bias. The corrective factor is the antilogarithm of the quotient of the variance of LADJ$ divided by two, that is 1.1312.

The equation can then be rewritten:

$$(2)\quad \text{CER 100 ADJ\$} = 0.42550\ e^{0.0879\text{MAXSP}}\ .\text{CRWF}^{0.57554}$$
$$\times\ .\text{SONAR}^{0.091}\ .e^{0.0025\text{ORD}}\ \text{SQYD}^{-0.102}$$

where:

ADJ$ = end cost adjusted to 1970

0.4255 = 0.376 x 1.1312

The other variables being the same as before.

CER 100 is an exponential equation that can be used to predict escort ship end costs from five explanatory variables that describe four performance characteristics and one production characteristic.

Just for curiosity, let us apply this equation to the FFG-7.

$$MAXSP = 29$$

$$CRWF = \frac{3605}{185} = 19.5$$

SONAR Index = 6.67

ORD = Gun & Missile = 13.46 + 165 = 178.46 (considering only Harpoon)

= 13.46 + 110 = 123.46 (considering only Standard)

SQYD = 1 (lead ship)

CER 100 will give us:

$$ADJ\$ = 0.42550\ e^{0.0879x29}\ .19.5^{0.57554}\ .6.67^{0.091}$$
$$x\ .e^{0.0025x178.46}\ .1$$
$$= 55.51 \text{ Mi (for Harpoon Missile)}$$
$$= 48.34 \text{ Mi (for Standard Missile)}$$

We can see the influence that the missile system can have in the costs. However, it must be taken into consideration that the value of ORD and SONAR are only tentative as some figures used for both the Harpoon and SQS 53 are not very reliable. In conclusion we can say that this model gives us a value coincident with the one developed in our study.

3. Results of the Secondary Analysis

The alternate methods considered in the secondary analysis have the objective of:

(1) Using displacement as an explanatory variable

(2) Derive estimating relationships to predict displacement as a function of escort ship performance and production variables

(3) Add nuclear powered escorts to the primary 100 ship

Displacement is now included as an explanatory variable for two reasons: first, because some users might be interested in estimating escort end costs based on separately derived estimates of displacement; second, the accuracy of CER's can be compared to those based on weight, normally a reliable predictor of cost.

Using full load displacement, the conclusion was reached that the log of end costs can be related to:

(1) Maximum speed

(2) Ln of full load displacement (LFLD)

(3) Ordnance Index (ORD)

(4) Ln of building sequence by shipyard and class (LSQYD)

The relationship obtained by regression analysis is:

$$\mathrm{LADJ\$} = 0.0087 + \underset{(6.83)}{0.0425}\ \mathrm{MAXSP} + \underset{(7.08)}{0.6234}\ \mathrm{LFLD} + \underset{(3.73)}{0.018}\ \mathrm{ORD} - \underset{(-4.31)}{0.0988}\ \mathrm{LSQYD}$$

F-statistic = 352.7

Multiple correlation coefficient (R^2) = 0.937

Standard error of the estimate (SE of Y/X) = 0.12731

Durbin-Watson statistic = 1.96

The values of the t-statistics, F-statistic and the Durbin-Watson are significant at the 95% confidence level. No serial correlation is present in the residuals.

$$\text{CER 100D ADJ\$} = 0.055831\ e^{0.04253\text{MAXSP}} \cdot \text{FLD}^{0.6235}$$
$$\times \cdot e^{0.0018235\text{ORD}} \cdot \text{SQYD}^{-0.09885}$$

where ADJ$ = end cost adjusted to 1970

$0.055831 = \exp -3.0087 \times e^{0.49652^2 \div 2}$

FLD = full load displacement in tons

The other explanatory variables have the same meaning as for CER 100.

We now have two equations for estimation of end costs of new escorts, CER and CER 100D where D indicates the presence of displacement as an explanatory variable. The main effect of including displacement as an explanatory variable is that two major performance variables, crew factor and the Sonar index are excluded from the equation. When LFLD enters the regression, LCRWF and LSONR are no longer significant variables. Thus, whenever CER 100D is used, the estimates are insensitive to the type of Sonar that the ship carries as well as to the characteristics related to the crew factor.

As the inclusion of full load displacement excludes the crew factor and the sonar index from the CER, analyses were conducted to derive relationships between the full load displacements of the 100 escorts and their performance characteristics. Two estimating relationships were developed: the first explaining displacement as a function of endurance at 20 knots, maximum speed, crew factor, sonar index and the ordnance index, while the second relationship explains displacement from the same five variables as well as the date at which each ship's keel was laid down.

The first relationship is:

$$\begin{aligned} LFLD = 3.4143 &+ \underset{(3.98)}{0.34688}\ LR/20 + \underset{(33.7)}{0.066014}\ MAXSP \\ &+ \underset{(6.41)}{0.83637}\ LCRWF + \underset{(10.2)}{0.094291}\ SONAR \\ &+ \underset{(4.09)}{0.000707}\ ORD \end{aligned}$$

where

LR/20 = ln endurance (in nautical miles) at 20 knots,

the other variables having been defined before.

F-statistic = 2.54.9

Multiple correlation coefficient (R^2) = 0.991

Standard error of the estimate = 0.04004

Durbin-Watson = 1.33

The values of the statistics are all significant at the 95% level of confidence. However, the value of the Durbin-Watson statistic reveals that serial correlation in the residuals probably exists. As the ships in the data were arranged in ascending order by time, some variable that is time related and not specified in the equation is the probable cause of this serial correlation. When the ships in the data were arranged in random order, no serial correlation shows up without change in the estimated values of the coefficients as well as their statistics.

Taking antilogarithms of both sides of the equation and correcting the resulting bias, the following equation was obtained:

$$\begin{aligned} FLD100 \quad FLD = 33.192\ R/20^{0.34688}\ .e^{0.066014\ MAXSP} \\ x\ .CRWF^{0.83636}\ .e^{0.009429\ SONAR}\ .e^{0.000707\ ORD} \end{aligned}$$

The second relationship is:

$$\begin{aligned} LFLD = 2.9379 &+ \underset{(2.21)}{0.20491}\ LR/20 + \underset{(35.6)}{0.06619}\ MAXSP + \\ &+ \underset{(7.52)}{1.0906}\ LCRWF + \underset{(2.65)}{0.0045106}\ SONAR \\ &+ \underset{(3.52)}{0.00058954}\ ORD + \underset{(3.37)}{0.01069}\ TIME \end{aligned}$$

where

TIME = the year in which each ship's keel was laid down, with 1 January 1949 equals 0.0 and each year thereafter is 1.00.

F-statistic = 1995.9

Multiple correlation coefficient (R^2) = 0.992

Standard error of the estimate (SE of Y/X) = 0.038

Durbin-Watson statistic = 1.50

Again all the statistics are significant at the 95% level of confidence. Taking antilogarithms, the following equation resulted:

$$\begin{aligned} \text{FLD100T} \quad FLD = 20.163\ R/20^{0.20491}\ .e^{0.06619\ MAXSP} \\ \times\ .CRWF^{1.0906}\ .e^{0.0045106\ SONAR} \\ \times\ .e^{0.00058954\ ORD}\ .e^{0.01069\ TIME} \end{aligned}$$

The T in FLD 100T indicates the presence of time as an explanatory variable, as opposed to its absence in FLD100. When TIME is included in FLD100T, the values of the exponents for R/20, CRWF, SONAR, and ORD change significantly. This is due to multicollinearity between TIME and these variables. Because of this multicollinearity, the effects of time were reflected in the exponents of R/20, CWRF, SONAR and ORD in FLD100. Theses effects were removed when TIME was added as an explanatory variable in FLD100T.

Two more types of estimating relationships were also derived including nuclear powered ships. As these relationships were not used in the FFG-7 study, they will not be explained in detail here. Table A-1 displays all the cost estimating relationships that were derived in ESCOMO.

Checking as it was done with the CER100, how the relationship CER100D works with the FFG-7, we get:

$$\begin{aligned}
MAXSP &= 29 \text{ knots} \\
CRWF &= 19.5 \text{ tons/man} \\
ORD &= 178.5 \text{ (Harpoon)} \\
& 123.5 \text{ (Standard Missile)} \\
FLD &= 3605 \text{ tons}
\end{aligned}$$

$$\begin{aligned}
ADJ\$ &= 0.055831.e^{0.04253\ MAXSP} .FLD^{0.6235} .e^{0.0018235\ ORD} \\
&= 43.82 \text{ Mi. (Harpoon)} \\
&= 40.0 \text{ Mi. (Standard)}
\end{aligned}$$

These costs are well below those found with the CER100. Using a speed of 30 knots, instead of 29, the cost for an ORD index of 160 (maximum of the curve of chapter 5) would be 43.99 Mi. We can conclude that CER100 seems more accurate than the CER100D.

The equations for displacement could not be tested as the endurance at 20 knots is now known. However, trying a few values, it seems that they would overestimate displacement. Also, some incorrect values were detected, a reason why both FLD and FLD100T should be used with care.

TABLE A-1

SUMMARY AND COMPARISON OF END COST ESTIMATING RELATIONSHIPS

CER	Data Base	CONSTANT	MAXSP	CRWF	FLD	SONAR	ORD	POWER	SQYD
CER100	100	0.425490	$e^{0.087984\ MAXSP}$	$CRWF^{0.57554}$		$SONAR^{0.090806}$	$e^{0.0025353\ ORD}$		$SQYD^{-0.102010}$
CER100D	100	0.055831	$e^{0.042529\ MAXSP}$		$FLD^{0.62348}$		$e^{0.0018235\ ORD}$		$SQYD^{-0.098846}$
CER102	102	0.437070	$e^{0.087516\ MAXSP}$	$CRWF^{0.57816}$		$SONAR^{0.087950}$	$e^{0.0025593\ ORD}$	$e^{0.90337\ POWER}$	$SQYD^{-0.101760}$
CER102D	102	0.059566	$e^{0.042778\ MAXSP}$		$FLD^{0.61607}$		$e^{0.0018633\ ORD}$	$e^{0.67683\ POWER}$	$SQYD^{-0.098755}$
CER103	103	0.289710	$e^{0.091459\ MAXSP}$	$CRWF^{0.72360}$		$SONAR^{0.088325}$	$e^{0.0020677\ ORD}$	$e^{0.89110\ POWER}$	$SQYD^{-0.105330}$
CER103D	103	0.026933	$e^{0.042308\ MAXSP}$		$FLD^{0.72698}$		$e^{0.0011059\ ORD}$	$e^{0.61590\ POWER}$	$SQYD^{-0.105870}$

where:
MAXSP = maximum speed in knots
CRWF = crew factor
FLD = full load displacement in tons
SONAR = sonar system index
ORD = ordnance (gun and missile) index
POWER = a dummy variable equal to one for nuclear ships and zero for conventional ships
SQYD = building sequence number by class and shipyard

FORM FOR UNIT PRICE ANALYSIS

UNIT PRICE ANALYSIS - BASIC CONSTRUCTION

NAVSHIPS 4202.2 (REV. 1-56)

BUDGET BUREAU . 95-R271

[illegible]	VESSEL	INVITATION NO. P.R.
[illegible]		NO. OF VESSELS COVERED BY THIS UNIT PRICE ANALYSIS

	ITEM	DIRECT LABOR HOURS	DIRECT LABOR DOLLAR	DIRECT MATERIAL 1/	OVERHEAD	TOTAL
A.	ESTIMATED COST*					
1	HULL STRUCTURE		$	$	$	$
2	PROPULSION					
3	ELECTRIC PLANT					
4	COMMUNICATION AND CONTROL					
5	AUXILIARY SYSTEMS					
6	OUTFIT AND FURNISHINGS					
7	ARMAMENT					
8	DESIGN AND ENGINEERING SERVICES					
8	CONSTRUCTION SERVICES					
B.	SUB-TOTAL - COST		$	$	$	$
C.	PROPOSED PROFIT (% OF LINE B)					
D.	GRAND TOTAL - UNIT PRICE					$

	1/ DIRECT MATERIAL BREAKDOWN	
A	DIRECT (Stores)	$
B	PURCHASED PARTS	
C	SUBCONTRACTS (Major)	
1		
2		
3		
4		
	TOTAL	$

This is to certify that the information herein is based upon or compiled from the books and records of this company and is accurate to the best of my knowledge and belief.

NAME OF FIRM	
ADDRESS	
BY (Name)	TITLE
SIGNATURE	DATE

* See definitions on reverse

UNIT PRICE ANALYSIS--BASIC CONSTRUCTION

APPENDIX C

LEARNING SLOPES BY SHIPBUILDER

CLASS	PR#	SHIPBUILDER	ELEMENT	DIRECT LABOR	MATERIAL	TOTAL COS
1. DD 931	523-19	Bath	1	96.8	96.8	92.7
			2	98.5	96.1	95.2
			3	98.7	95.5	94.7
			4	98.7	96.8	93.7
			5	98.7	96.8	94.9
			6	98.1	96.8	93.4
			7	98.7	96.8	93.9
			8	67.3	50.2	52.8
			9	98.7	96.8	93.6
			Total	97.8	91.3	91.0
2. DE 1040	523-21280	Ingalls	1	97.0	95.4	96.6
			2	97.1	97.6	97.6
			3	97.0	96.4	96.5
			4	97.0	97.4	97.2
			5	97.1	98.2	97.7
			6	97.0	97.2	97.1
			7	97.0	88.0	90.1
			8	55.2	56.1	55.5
			9	89.2	91.4	89.5
			Total	92.0	96.3	94.2
3. DEG 1	523-21281	National	1	87.7	98.6	88.3
			2	96.0	99.7	99.1
			3	96.0	96.4	96.4
			4	96.0	96.2	95.8
			5	96.0	99.4	96.7
			6	96.0	98.6	96.7
			7	96.0	100.	97.6
			8	56.9	36.7	52.2
			9	95.7	95.6	92.0
			Total	88.0	97.3	92.0

CLASS	PR#	SHIPBUILDER	ELE-MENT	DIRECT LABOR	MATERIAL	TOTAL CC
4. DDG2	523-52	New York	1	102.1	99.2	99.1
			2	99.1	99.2	99.2
			3	99.1	99.2	99.2
			4	99.1	99.3	99.2
			5	99.1	99.2	99.2
			6	99.1	99.2	99.2
			7	99.1	99.2	99.1
			8	53.9	99.7	56.1
			9	99.1	99.3	99.1
			Total	96.5	95.5	97.8
5. DLG 26	523-21286	Defoe	1	97.1	99.2	92.7
			2	97.1	98.2	95.7
			3	97.1	98.6	95.3
			4	97.1	98.6	90.6
			5	97.1	98.6	92.8
			6	97.1	98.6	91.7
			7	97.1	99.7	93.0
			8	56.0	100.0	58.1
			9	97.1	98.6	88.5
			Total	95.6	98.5	92.6
6. DD 931	523-19	Newport	1	93.4	96.7	93.8
			2	95.3	97.7	97.1
			3	95.6	99.3	98.1
			4	96.2	99.4	97.0
			5	96.1	93.2	96.8
			6	96.4	99.8	97.1
			7	95.8	100.0	97.5
			8	52.8	50.3	52.7
			9	94.1	94.2	93.2
			Total	91.7	97.5	94.5

CLASS	PR#	SHIPBUILDER	ELE-MENT	DIRECT LABOR	MATERIAL	TOTAL C(
7. DE 1040	523-21280	Puget	1	96.2	100.0	97.4
			2	91.8	99.7	97.9
			3	91.2	100.0	97.3
			4	95.5	99.5	97.6
			5	92.1	96.3	95.0
			6	97.0	99.4	99.0
			7	91.7	99.7	95.1
			8	59.1	70.0	61.8
			9	90.5	96.9	92.3
			Total	92.0	98.0	96.0
8. DDG 2	523-52	Avondale	1	92.4	98.8	95.8
			2	92.4	99.6	93.5
			3	92.4	99.6	98.3
			4	92.5	99.6	95.3
			5	92.4	99.6	97.1
			6	92.4	99.6	96.1
			7	87.8	99.6	97.7
			8	50.0	50.0	50.0
			9	92.4	99.6	93.2
			Total	89.0	99.5	95.3
9. DDG 2	523-54	Bath	1	97.0	93.9	97.0
			2	96.9	97.7	97.3
			3	97.6	98.2	97.7
			4	97.6	97.1	96.6
			5	97.6	97.8	97.0
			6	97.9	98.3	97.2
			7	97.6	98.7	96.9
			8	60.8	78.0	56.9
			9	98.2	98.9	97.2
			Total	95.0	97.5	95.5
10. DLG 16	523-48.1	Ingalls	1	97.6	99.7	97.2
			2	97.6	97.5	97.4
			3	97.6	98.4	97.5
			4	97.6	99.3	97.4
			5	97.6	98.8	97.6
			6	97.6	98.7	98.0
			7	97.6	91.0	93.4
			8	57.3	54.5	56.7
			9	84.9	87.0	84.4
			Total	94.0	97.5	95.4

		DIRECT LABOR HOURS	MATERIAL DOLLARS	TOTAL COST
DD931	Bath P. R. 523-19			
	Avg. Slope of Eight Groups (1-7,9)	98.36	96.55	94.01
	Standard Deviation	.665	.490	.849
	Minimum	96.8	95.5	92.7
DE1040	Ingalls P. R. 523-21280			
	Avg. Slope of Eight Groups (1-7,9)	96.05	95.20	95.29
	Standard Deviation	2.768	3.613	3.417
	Minimum	89.2	88.0	89.5
	Maximum	97.1	98.2	97.7
DEG1	National P. R. 523-21281			
	Avg. Slope of Eight Groups (1-7,9)	94.80	97.94	95.33
	Standard Deviation	2.905	1.960	3.485
	Minimum	87.7	94.6	88.3
	Maximum	96.0	100.0	99.1
DDG2	New York P. R. 523-52			
	Avg. Slope of Eight Groups (1-7,9)	99.48	99.23	99.16
	Standard Devaiation	1.061	.047	.052
	Minimum	99.1	99.2	99.1
	Maximum	102.1	99.3	99.2
DLG26	Defoe P. R. 523-21286			
	Avg. Slope of Eight Groups (1-7,9)	97.10	98.76	92.54
	Standard Deviation	0.00	.466	2.351
	Minimum	97.1	98.2	88.5
	Maximum	97.1	99.7	95.7

		DIRECT LABOR HOURS	MATERIAL DOLLARS	TOTAL COST
DD931	Newport News P.R. 523-19			
	Avg. Slope of Eight Groups (1-7,9)	95.36	98.16	96.34
	Standard Deviation	1.070	1.961	1.770
	Minimum	93.4	94.2	93.3
	Maximum	96.4	100.0	98.1
DE1040	Puget Sound P.R. 523-21280			
	Avg. Slope of Eight Groups (1-7,9)	93.25	98.94	96.45
	Standard Deviation	2.547	1.467	2.161
	Minimum	90.5	96.3	92.3
	Maximum	97.0	100.0	99.0
DDG2	Avondale P.R. 523-52			
	Avg. Slope of Eight Groups (1-7,9)	91.84	99.5	96.50
	Standard Deviation	1.632	.283	1.774
	Minimum	87.8	98.8	93.2
	Maximum	92.5	99.6	98.5
DDG2	Bath P.R. 523-54			
	Avg. Slope of Eight Groups (1-7,9)	97.55	98.20	97.11
	Standard Deviation	.428	.639	.323
	Minimum	96.9	97.1	96.6
	Maximum	98.2	98.9	97.7

APPENDIX D

Means by Class and Their Standard Deviations

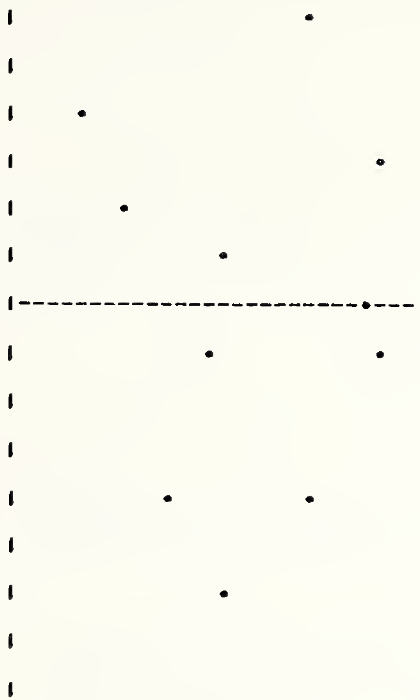
	DIRECT LABOR HOURS						MATERIAL DOLLARS						TOTAL DOLLARS					
	Total		T-8		8		T		T-8		8		T		T-8		8	
Ship Class	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
AE 21	90.3		94.5		52.1		96.8		97.3		50.0		94.8		96.2		50.0	
25	94.8	3.74	96.8	2.19	68.9	22.51	96.6	2.17	98.0	.35	58.1	7.08	95.2	2.06	97.1	1.91	59.7	9.26
26	95.2		96.3		56.0		92.6		93.8		51.9		92.8		94.1		52.9	
AFS 1	94.6	2.11	96.7	2.00	53.3	5.77	96.4	2.42	97.5	1.88	55.4	7.74	95.7	2.03	97.1	1.73	53.8	6.30
AGOR 3	91.1	3.15	96.6	2.33	65.5	18.0	97.3	1.86	98.4	1.27	60.4	14.21	95.5	1.47	97.6	1.11	58.5	10.26
AKA 113	90.3	2.21	94.4	1.16	53.3	3.61	97.4	1.79	98.2	1.80	52.0	2.35	93.8	.99	96.5	1.42	53.2	4.41
AOR 1	96.6		98.1		63.5		95.1		95.5		56.0		95.7		96.7		61.2	
DD 931	94.3	2.62	96.2	1.57	61.2	7.68	95.9	2.73	97.9	.97	50.2	2.07	93.9	1.66	95.9	.92	55.1	4.92
DE 1040	93.2	3.48	95.4	2.72	62.8	13.75	97.8	1.93	98.3	1.78	63.5	19.44	95.1	3.29	96.5	2.86	63.1	13.15
1052	91.7	4.30	93.1	4.76	67.1	9.70	98.4	1.33	98.5	1.36	86.3	19.60	94.9	2.49	95.7	2.73	68.6	9.35
DEG 1	91.5	4.06	94.3	3.18	60.1	14.40	97.2	2.20	97.8	2.28	63.1	20.93	93.3	3.93	95.0	3.62	60.2	14.08
DDG 2	93.6	3.10	96.4	2.03	60.0	10.36	98.1	1.46	98.7	1.24	68.1	20.38	95.3	1.94	97.1	1.49	58.8	8.16
DLG 16	93.5	.61	95.7	1.16	59.0	4.94	97.4	1.22	97.9	.88	58.4	6.75	94.8	1.18	96.1	1.32	58.1	4.54
26	92.6	2.03	94.9	1.88	59.8	11.58	98.1	.82	98.7	.69	60.2	16.10	94.8	1.67	96.4	1.21	58.4	8.63
LCU 1610	96.1	3.26	97.0	2.80	80.3	24.78	97.6	2.90	99.8	.27	65.2	23.42	96.5	2.18	98.7	1.23	68.6	21.80
1620	100.0		100.0				100.0		100.0				100.0		100.0		100.0	
LSD 29	91.1	4.23	93.7	4.01	50.3	.52	98.7	.47	99.1	.21	50.9	1.01	95.2	1.57	96.8	1.47	50.4	.40
36	90.0	3.57	93.4	2.64	51.7	.67	96.6	1.23	97.0	1.30	56.2	6.41	93.1	8.76	95.3	2.05	55.1	1.75
LST 1179	92.0	1.77	93.6	1.84	58.3	5.98	97.9	1.24	98.2	1.05	63.5	11.18	95.1	.99	96.2	.74	59.2	5.43
LPD 7	94.1	2.13	96.2	1.74	58.6	9.23	97.1	.71	97.6	.76	54.6	4.94	95.0	1.50	96.5	1.01	57.9	8.63
MSC 268	92.1	4.8	92.5	5.05	80.2	16.96	98.9	1.12	99.0	1.12	79.7	23.58	96.8	1.69	97.0	1.82	76.1	16.05
289	93.9		100.0		50.0		99.3		99.9		50.0		97.8		99.9		50.0	
291	94.0	4.66	94.9	4.29	78.0	17.01	98.5	.55	99.1	.52	76.6	23.20	95.3	3.96	97.3	1.76	76.3	18.56
MSI 15	86.9	16.76	87.4	17.89	80.2	4.39	96.7	1.27	96.7	1.34	100.0		93.3	4.95	93.7	4.95	84.0	.35
PGM 71	93.7		93.0		100.0		100.0		100.0		100.0		97.5		97.3		100.0	
SSBN 609	92.9	10.32	94.3	8.06	83.1	38.54	98.9	.21	99.1	.35	69.5	17.54	93.9	7.57	95.1	5.73	80.8	34.79
640	95.1	.99	96.9	1.03	76.5	14.86	100.0	1.94	100.0	1.87	63.8	12.37	96.0	.67	97.9	1.07	74.7	13.40
SSN 593	92.0	3.13	96.0	2.34	58.3	7.98	97.1	1.27	97.5	1.07	67.2	13.02	93.6	1.94	96.6	1.66	59.1	9.18
637	95.5	2.22	97.6	.90	74.6	14.30	98.7	1.20	99.0	1.13	71.8	16.86	95.9	1.97	97.6	1.19	73.1	12.29

```
      COST← 18.07 25.19 27.93 36.06 43.7 56.06 71.34 75.97 74.56 30.94 65.22
      ⍴COST

11

      IND←16.2 71.4 100.8

      IND←16.2 71.4 90.8 152.8 70.3 168 217.1 253.6 259.4 140.8 216.5

      ⍴IND

11

      SF←27.2 26.0 28.0 28.0 34.8 34 34.5 32.5 33 28 30

      ⍴SF

11

      COMP←170 196 240 248 293 350 375 396 418 245 296

      ⍴COMP

11

      VV←COST REGRESS LL
REGRESSION SS: 4323.449161   N=11

ERROR SS: 130.2868027   TOTAL SS: 4453.735964

RESIDUAL VARIANCE: 18.61240038

R SQUARE: 0.9707466263

        BETA   T-STATISTICS
      ¯56.625        ¯2.6283

        0.2074        3.7537
        2.6341        2.1891
       ¯0.0225       ¯0.2675
DO YOU WANT A PRINTOUT OF THE VAR-COV MATRIX?

Y
VARIANCE-COVARIANCE MATRIX:

   4.6417E+2  ¯7.6180E¯1  ¯2.4840E+1   1.4011E00
  ¯7.6180E¯1   3.0517E¯3   5.1642E¯2  ¯4.3472E¯3
  ¯2.4840E+1   5.1642E¯2   1.4479E00  ¯9.2603E¯2
   1.4011E00  ¯4.3472E¯3   9.2603E¯2   7.0981E¯3
F RATIO: 77.42954646   DF ARE: 3 AND 7
DURBIN-WATSON: 1.667346079
DO YOU WANT TO FORECAST A VALUE OF Y?
N
```

```
W←CORRELATION LL

   W      1.0     2.0     3.0
 1.0      1.0     0.525   0.876
 2.0      0.525   1.0     0.835
 3.0      0.876   0.835   1.0


   ⍝ REMOVING COMPLEMENT AS VARIABLE

   L←⍉2 11⍴(IND,SF)


   ZX←COST REGRESS L
REGRESSION SS: 4322.117121    N=11
ERROR SS: 131.6188426    TOTAL SS: 4453.735964
RESIDUAL VARIANCE: 16.45235533
R SQUARE: 0.9704475425
          BETA    T-STATISTICS
      ¯52.1762        ¯4.0515
        0.1936        10.4337
        2.3401         5.0824
DO YOU WANT A PRINTOUT OF THE VAR-COV MATRIX?
Y
VARIANCE-COVARIANCE MATRIX:
   1.6585E+2    8.5085E¯2   ¯5.8002E00
   8.5085E¯2    3.4416E¯4   ¯4.4826E¯3
  ¯5.0002E00   ¯4.4826E¯3    2.1199E¯1
F RATIO: 131.3525339    DF ARE: 2 AND 8
DURBIN-WATSON: 1.650377947
DO YOU WANT TO FORECAST A VALUE OF Y?
N
```

```
∩ LET US EXAMINE THE VALUES OF ZX AND RESIDUALS
ZX
13.71346082        4.35653918
23.48531697        1.704683031
32.15268179       ¯4.222681792
42.2848825        ¯6.224082498
42.82648988        0.8735101158
59.90842639       ¯3.848426386
70.94174442        0.3982555799
72.92213163        3.047868373
75.27408035       ¯0.7140803457
39.94668234       ¯1.006682335
59.58410292        5.635897077


      RES+SCAT ZX
RANGE OF X: 0  80
RANGE OF Y: ¯8  6
```

RES



```
⍝ NO PATTERN IS EVIDENT, HENCE LOOK AT THE CORRELATION MATRIX⍝
W←CORRELATION L
W
        1.0     2.0
1.0     1.0     0.509
2.0     0.509   1.0

⍝ LET US ADJUST COSTS FOR THE SPEED OF 30 KNOTS
```

```
      F←2.3401 × (30-SP)

      ACOST←COST÷F

      ⍝ WRITE COSTS ADJUSTED FOR SPEED

      ACOST

24.62228  34.5504  32.6102  40.7402  32.46752  46.6996  60.80955  70.12
1975  67.5397  43.6202  65.22


      V←ACOST REGRESS L

REGRESSION SS: 2471.804522   N=11
ERROR SS: 131.6188426   TOTAL SS: 2603.423365

RESIDUAL VARIANCE: 16.45235533

R SQUARE: 0.9494439343
              BETA    T-STATISTICS
           18.0268          1.3998
            0.1936         10.4337

DO YOU WANT A PRINTOUT OF THE VAR-COV MATRIX?

N
F RATIO: 75.12008077   DF ARE: 2 AND 8
DURBIN-WATSON: 1.658377947
DO YOU WANT TO FORECAST A VALUE OF Y?
N


      V←ACOST REGRESS IND

REGRESSION SS: 2471.804522   N=11

ERROR SS: 131.6188427   TOTAL SS: 2603.423365

RESIDUAL VARIANCE: 14.62431585

R SQUARE: 0.9494439343

              BETA    T-STATISTICS
           18.0263          7.1486

            0.1936         13.0008

DO YOU WANT A PRINTOUT OF THE VAR-COV MATRIX?

VARIANCE-COVARIANCE MATRIX:

    6.3587E00  ¯3.3389E¯2

   ¯3.3309E¯2   2.2166E¯4
F RATIO: 169.0201817   DF ARE: 1 AND 9

DURBIN-WATSON: 1.658357964
DO YOU WANT TO FORECAST A VALUE OF Y?
N
```

```
⍝ LET US CHSCK THE REGRESSION ASSUMING THE COST OF THE DD963 IS 75 MI (ADJ. FOR SPEED)

      ZW←COST REGRESS L
REGRESSION SS: 4545.283925   N=11
ERROR SS: 323.266293   TOTAL SS: 4868.550218
RESIDUAL VARIANCE: 40.40828662
R SQUARE: 0.9336011177
             BETA    T-STATISTICS
         ¯50.4025          ¯2.5224
           0.2097           7.1501
           2.2192           3.1114
DO YOU WANT A PRINTOUT OF THE VAR-COV MATRIX?
Y
VARIANCE-COVARIANCE MATRIX:
   3.9928E+2    1.9366E¯1   ¯1.3918E+1
   1.9366E¯1    8.5998E¯4   ¯1.0632E¯2
  ¯1.3918E+1   ¯1.0632E¯2    5.0871E¯1
F RATIO: 56.24197789   DF ARE: 2 AND 8
DURBIN-WATSON: 1.461622124
DO YOU WANT TO FORECAST A VALUE OF Y?
N


      SP←¯1↓SP
      SP←SP,31
      SP
27.2  26  28  28  34.8  34  34.5  32.5  33  28  31

      SL←⍉2 11⍴(IND,SP)


      ZL←COST REGRESS SL
REGRESSION SS: 4603.980913   N=11
ERROR SS: 264.5693047   TOTAL SS: 4868.550218
RESIDUAL VARIANCE: 33.07116309
R SQUARE: 0.9456574765
             BETA    T-STATISTICS
         ¯55.8778          ¯3.0429
           0.2029           7.5133
           2.4249           3.6883
DO YOU WANT A PRINTOUT OF THE VAR-COV MATRIX?
Y
VARIANCE-COVARIANCE MATRIX:
   3.3720E+2    1.7895E¯1   ¯1.1799E+1
   1.7895E¯1    7.2949E¯4   ¯9.4710E¯3
  ¯1.1799E+1   ¯9.4710E¯3    4.3225E¯1
F RATIO: 69.60718165   DF ARE: 2 AND 8
DURBIN-WATSON: 1.366741150
DO YOU WANT TO FORECAST A VALUE OF Y?
N
```

```
⍝ LET US NOW RESTRICT OURSELVES TO MISSILE SHIPS
      MCOST←36.06 56.06 71.34 75.97 74.33 38.94 65.3
      ⍴MCOST
7
      ⍞MIND←152.8 15
      MIND←152.8 168 217.1 253.6 259.43 140.8 216.5
      ⍴MIND
7
      MSP←28.0 34. 34.5 32.5 33 28 30
      ⍴MSP
7
      ML←⍉2 7⍴(MIND,MSP)
      MZX←MCOST REGRESS ML
REGRESSION SS: 1592.268538   N=7
ERROR SS: 56.40623343   TOTAL SS: 1648.674771
RESIDUAL VARIANCE: 14.10155836

R SQUARE: 0.9657869251
         BETA    T-STATISTICS
      ¯55.7535       ¯3.0565

        0.2599        6.562

        2.0104        2.9144
DO YOU WANT A PRINTOUT OF THE VAR-COV MATRIX?
Y
VARIANCE-COVARIANCE MATRIX:

   3.3273E+2   1.8840E¯1  ¯1.1729E+1
   1.8848E¯1   1.5686E¯3  ¯1.6038E¯2
  ¯1.1729E+1  ¯1.6038E¯2   4.7586E¯1
F RATIO: 56.45718359   DF ARE: 2 AND 4
DURBIN-WATSON: 1.302587484
DO YOU WANT TO FORECAST A VALUE OF Y?
N
      MW←CORRELATION ML

      MW

             1.0      2.0

      1.0    1.0      0.587

      2.0    0.587    1.0
```

```
⍝ TRYING TO CHECK FOR SERIAL CORRELATION

SEQ←1 2 3 4 5 6 7

MML←⍉3 7⍴(MIND,MSF,SEQ)

MMM←MCOST REGRESS MML

REGRESSION SS: 1624.399   N=7

ERROR SS: 24.27577177   TOTAL SS: 1648.674771

RESIDUAL VARIANCE: 8.091923922

R SQUARE: 0.9852755849

        BETA   T-STATISTICS

   ¯71.9746        ¯4.4879

     0.2234         6.3529

     2.5969         4.33

     1.2842         1.9927

DO YOU WANT A PRINTOUT OF THE VAR-COV MATRIX?

Y

VARIANCE-COVARIANCE MATRIX:

   2.5720E+2   2.5739E¯1  ¯9.1265E00  ¯5.2463E00

   2.5739E¯1   1.2362E¯3  ¯1.4599E¯2  ¯1.1814E¯2

  ¯9.1265E00  ¯1.4599E¯2   3.5969E¯1   1.8969E¯1

  ¯5.2463E00  ¯1.1814E¯2   1.8969E¯1   4.1535E¯1

F RATIO: 66.91441225   DF ARE: 3 AND 3

DURBIN-WATSON: 2.078636092

DO YOU WANT TO FORECAST A VALUE OF Y?

N
```

```
⍝ THERE IS REALLY SOME SERIAL CORRELATION AS IT IS PROVED BY THE VALUE OF D-W WHICH IS ABOUT 2. , NOW .

⍝ HOWEVER THE EFFECT OF SERAAL CORELATION WIIL NOT BE CONSIDERED

⍝ LET US ADJUST FOR SPEED

  MF← 2.0104 × ( 30- MSP)

  MACOST←MCOST+MF

  ZXAL←MACOST REGRESS ML

REGRESSION SS: 926.4532375    N=7

ERROR SS: 56.40623343    TOTAL SS: 982.8594709

RESIDUAL VARIANCE: 14.10155836
R SQUARE: 0.9426100729
           BETA    T-STATISTICS

         4.5585          0.2499

         0.2599          6.562
         0.0             0.0

DO YOU WANT A PRINTOUT OF THE VAR-COV MATRIX?

N

F RATIO: 32.84932112    DF ARE: 2 AND 4

DURBIN-WATSON: 1.302587484

DO YOU WANT TO FORECAST A VALUE OF Y?
N



      VL←MACOST REGRESS MIND
REGRESSION SS: 926.4532375    N=7

ERROR SS: 56.40623343    TOTAL SS: 982.8594709
RESIDUAL VARIANCE: 11.28124669

R SQUARE: 0.9426100729


           BETA    T-STATISTICS
         4.5584          0.7716
         0.2599          9.0622

DO YOU WANT A PRINTOUT OF THE VAR-COV MATRIX?


N
F RATIO: 82.1233028    DF ARE: 1 AND 5
DURBIN-WATSON: 1.302584735
```

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